Semiconductors, 2022, Vol. 56, No. 13

# Monopolarity of hot charge carrier multiplication in $A^{III}B^{V}$ semiconductors at high electric field and noiseless avalanche photodiodes (a Review)

© M.P. Mikhailova, A.P. Dmitriev, I.A. Andreev, E.V. Ivanov¶, E.V. Kunitsyna, Yu.P. Yakovlev

Ioffe Institute,
194021 St. Petersburg, Russia

¶ E-mail: Ed@mail.ioffe.ru

Received June 10, 2021
Revised June 25, 2021
Accepted June 25, 2021

The results of theoretical and experimental studies of impact ionization processes and charge carrier heating in multi-valley $A^{III}B^{V}$ semiconductors at high electric field are presented and their relationship with the features of the band structure is discussed. A role of subsidiary $L$- and $X$-valleys, complex structure of the valence band and orientation dependence of the ionization coefficients are taken into account. A new approach to the choice of semiconductor materials with a large ratio of the ionization coefficients of holes and electrons to create the noiseless avalanche photodiodes due to monopolarity of hot charge carrier multiplication is proposed.

**Keywords:** impact ionization, multi-valley semiconductors, band structure, monopolarity of multiplication, avalanche photodiodes.

DOI: 10.21883/SC.2022.13.53893.9701

## 1. Introduction

For many years, intense studies have been carried out for processes of impact ionization in the semiconductors [1–6]. This is caused not only by the importance of studying fundamental physical phenomena related to heating the charge carriers in the high electric field [5–7], but necessity of creating a number of the semiconductor instruments for systems of the fiber-optic communication lines (FOCL), the high-frequency electronics, laser range finding, communication in free space, etc. [8–12]. Besides, the impact ionization phenomenon can be used for improving characteristics of light-emitting structures and devices based thereon (light-emitting diodes, lasers) in order to improve the quantum efficiency and increase the output optical power [13].

The first avalanche photodetectors designed to operate within the spectral range $1.3-1.55\,\mu$m were based on Ge and Si and described in the monographs [7,8,14]. However, the requirement of developing the avalanche photodetectors for the near- and mid-infrared regions of $2-5\,\mu$m has attracted researchers to the $A^{III}B^{V}$ semiconductor compounds (GaAs, InAs, InSb, GaSb, InP, AlSb) and their solid solutions [15].

The avalanche photodiodes (APD) for the FOCL systems and high-frequency detection must comply with a number of important requirements: high amplification, a large ratio of the ionization coefficients of electrons and holes, low dark currents, high response rate, a low level of excessive noise [2–4,7,10–12]. For the last twenty years, the studies for creation and improvement of these devices have been actively carried out in many research centers of USA, Great Britain, France, Germany, Japan, China and in Russia as well [8,14,15]. Extensive experimental and theoretical studies of employees of the Ioffe Institute play a significant role among these studies [5,6,9,13,15–19].

The main result of these studies was new understanding of the fundamental physical processes of the impact ionization and establishing their relation to a band structure of the semiconductor materials. It has been demonstrated that energy band diagrams of the multi-valley $A^{III}B^{V}$ semiconductors are advantageous in creating low-noise, practically noiseless APDs designed to operate in the near- and mid-infrared ranges. It has been established that this task is to be solved by applying two physical effects — monopolarity multiplication of the charge carriers and low threshold energy of ionization due to the band „resonance“ phenomenon, i.e. a closeness of the band gap value and the value of spin-orbit splitting of the valence band. This conclusion was confirmed by a big number of the studies and creation of an APD model based on the GaInAsSb/GaAlAsSb solid solutions with separated regions of absorption and multiplication. It was tested in an optoelectronic receiving module designed to record the radiation of the pulse lasers.

This review presents a new approach to selecting materials for developing the APD with the large ratio of the ionization coefficients and the low level of excessive noise.

## 2. Impact ionization in the high electric field

The process of interband impact ionization and multiplication of the charge carriers, i.e. creation of the electron-hole pairs is caused by the Coulomb interaction of electrons and determined by a type of a distribution function of hot carriers in the electric field and a value of the threshold ionization energy [1,4,5,8]. A process, in which the ionizing particle is a hot electron from the conductivity band, is called electron impact ionization. If the ionization is caused by a hole from the valence band or the spin-orbit split-off band, then we say about hole ionization. The coefficient of impact ionization is determined as a reciprocal value of the average distance, which must be covered by the charge carrier along the electric field to create the electron-hole pair. The impact ionization is usually done by the charge carrier, which has reached the threshold ionization energy $\varepsilon_{ie}$ and $\varepsilon_{ih}$ for the electron and hole, respectively. Its value depends on the band gap $E_g$ and values of the effective masses of the charge carriers [8]. In case of two parabolic bands, this energy for electrons is determined as

$$\varepsilon_{ie} = \left[1 + m_e/(m_e + m_h)\right] E_g, \tag{1}$$

and for the heavy holes it is equal to

$$\varepsilon_{ih} = \left[1 + m_h/(m_e + m_h)\right] E_g, \tag{2}$$

where $m_e$ and $m_h$ — effective masses of the electron and the hole, respectively. If $m_e \ll m_h$, then the values of the threshold energy for the electrons and the holes will be equal to

$$\varepsilon_{ie} \approx E_g, \quad \varepsilon_{ih} \approx 2E_g. \tag{3}$$

In case of the multi-valley semiconductors with a complex structure of the valence band, taking into account the spin-orbit split-off band with the energy $\Delta$ for the ionization by the hole, we obtain

$$\varepsilon_{ih} = \left[1 + m_{so}(1 - \Delta/E_g)/(2m_h - m_{so} + m_e)\right] E_g, \tag{4}$$

where $m_{so}$ — an effective mass of the hole from the spin-orbit split-off band.

Let us consider a relation of the main characteristics of the avalanche photodiodes with multiplication coefficients. The avalanche multiplication of the charge carriers is a process of creating the electron-hole pairs in the electric field, which are generated due to the impact ionization by the hot carriers. The multiplication coefficient of the electrons $M_e$, and the holes $M_h$, are defined as a ratio of the current flowing through the APD in presence of avalanche multiplication to the current value without avalanche:

$$M_e = I_e(w)/I_e(0), \quad M_h = I_h(w)/I_h(0), \tag{5}$$

where $w$ — a width of space charge region. The multiplication coefficients are usually measured when illuminating the $p{-}n$-junction (at $p$- or $n$-side) by strongly absorbed radiation, thereby allowing determining a value of the photocurrent, which is multiplied by minority carriers — electrons in the $p$-region or holes in the $n$-region.

The relationships between the values of multiplication coefficients and the coefficients of ionization of electrons $\alpha$, and holes, $\beta$, were derived in the papers [8,20]:

$$1 - 1/M_e = \int \alpha(x) \exp\left[-\int (\alpha - \beta)\, dx'\right] dx, \tag{6}$$

$$1 - 1/M_h = \int \beta(x) \exp\left[-\int (\alpha - \beta)\, dx'\right] dx. \tag{7}$$

For the sharp $p{-}n$-junctions it results in the field dependence of the ionization coefficients of the following kind:

$$\beta(E_m) = (1/M_e)(dM_h/dw), \tag{8}$$

$$\alpha(E_m) = \beta(E_m) + (d/dw)[\ln(M_e/M_h)], \tag{9}$$

where $E_m$ — the maximum value of the electric field in the $p{-}n$-junction.

The maximum amplification, response rate, the multiplication coefficient $M$ and the frequency band width $B$, as well as APD noise are heavily dependent on the ratio of the ionization coefficients $k = \beta/\alpha$. The statistical parameters of the avalanche multiplication process were considered independently in the papers [11,12]. It was shown that if the charge carriers are moving in the high electric field, when the impact ionization process involves both electrons and holes, then the avalanche consisting in two opposite fluxes of ionizing particles has a positive feedback, which results in the increase in current fluctuations and excessive noise [10].

The noise value in the unit frequency band is described by the relationship

$$\langle i^2 \rangle = 2eI_{\text{ph0}} \langle M^2 \rangle F, \tag{10}$$

where $I_{\text{ph0}}$ — an avalanche initiating photocurrent, $F$ — the coefficient (factor) of excessive noise, and the brackets $\langle\ \rangle$ mean averaging. The coefficient of excessive noise is a measure of degradation of the real APD in comparison with the ideal noiseless photodiode with the monopolarity multiplication of charge carriers: $F(M) = \langle M^2 \rangle / \langle M \rangle^2$. The value of the parameter $F$ depends on selection of a photodetector material, the ratio of the ionization coefficients and the APD design.

If the avalanche-like process is determinative, i.e. each injected charge carrier is subjected to the same multiplication $M$, the factor of excessive noise is equal to unity $(F = 1)$ and the measured noise $\langle i^2 \rangle$ is equal to just a value of shot noise. Some charge carriers with different amplification have an average multiplication coefficient $\langle M \rangle$. In the paper [21], Tager demonstrated that in case of the same ionization coefficients the spectral noise density must be in average in $M$ times higher than in case when one of them is much bigger than the other. If $\alpha = \beta$, there is a positive feedback in the avalanche, which greatly increases the multiplication fluctuations and results in the excessive noise. That is why one of the main requirements to APD is a large asymmetry of the coefficients of ionization of the charge carriers.

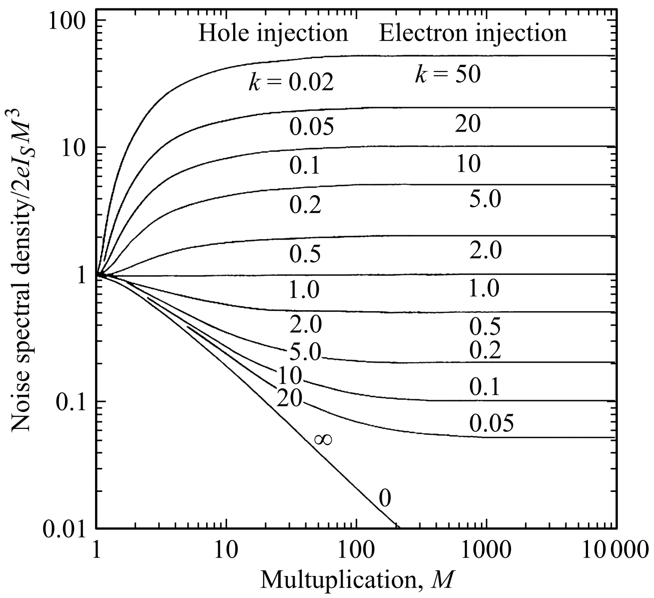


**Figure 1.** Dependence of the noise spectral density rated to $2eI_SM^3$, where $I_S$ — injection current, on the average multiplication coefficient $M$, which is calculated for various values of the ratio of the ionization coefficients $k = \beta/\alpha$ for the electron or hole injection [12].

In the paper [12], McIntyre obtained expressions relating the factor of excessive noise and the ratio of the ionization coefficients of electrons and holes $k = \beta/\alpha$:

$$F_e = M_e\{1 - (1 - k)[(M_e - 1)/M_e]^2\} \tag{11}$$

for electron injection,

$$F_h = M_h\{1 - (1 - 1/k)[(M_h - 1)/M_h]^2\} \tag{12}$$

for hole injection.

Fig. 1 shows the dependence of the noise spectral density on the average multiplication coefficient for various values of the ratio of the ionization coefficients. As it is clear, the lowest noise of avalanche is reached, when the parameter $k$ takes either very big or very small values provided that the avalanche is initiated by the charge carrier with the highest ionization coefficient (i.e. $\alpha \gg \beta$ or $\beta \gg \alpha$).

The response rate of the avalanche process and the product of the multiplication coefficient to the band width, $M \times B$, depends on a drift time of the carriers through the space charge region $\tau_i = w/V_{\text{dr}}$ (where $V_{\text{dr}}$ — the drift velocity) and the ratio of the ionization coefficients $k = \beta/\alpha$:

$$M \times B = 1/\tau_i \approx 1/k(w/V_{\text{dr}}) \quad \text{at} \quad k \ll 1. \tag{13}$$

## 3. Anisotropy of the ionization coefficients of electrons in the multi-valley semiconductors of the GaAs and InP type

In the $A^{III}B^{V}$ semiconductors of the GaAs, GaSb, InP type and their solid solutions the conductivity band is highly anisotropic (see Fig. 2) [22,23]. In particular, the direction (111) in the central Γ-valley has no state with the energy of an order of the impact ionization threshold $\varepsilon_{ie} \approx E_g$. Beside the central Γ-valley, these semiconductors have subsidiary $L$- and $X$-valleys, located in terms of the energy by $\Delta_L$ and $\Delta_X$ higher than the bottom of the Γ-valley, wherein $\Delta_L$, $\Delta_X < E_g$. In this situation, the main mechanism for the scattering of electrons with the energy $\varepsilon > \Delta_L$, $\Delta_X$ in the Γ-valley is intervalley scattering [7,23–28]. This character of the band structure substantially affects a kind of the distribution function at the high energies. The strong anisotropy of the energy spectrum results in the anisotropy of the distribution function and, therefore, to the anisotropy of the coefficient of impact ionization of the electrons.

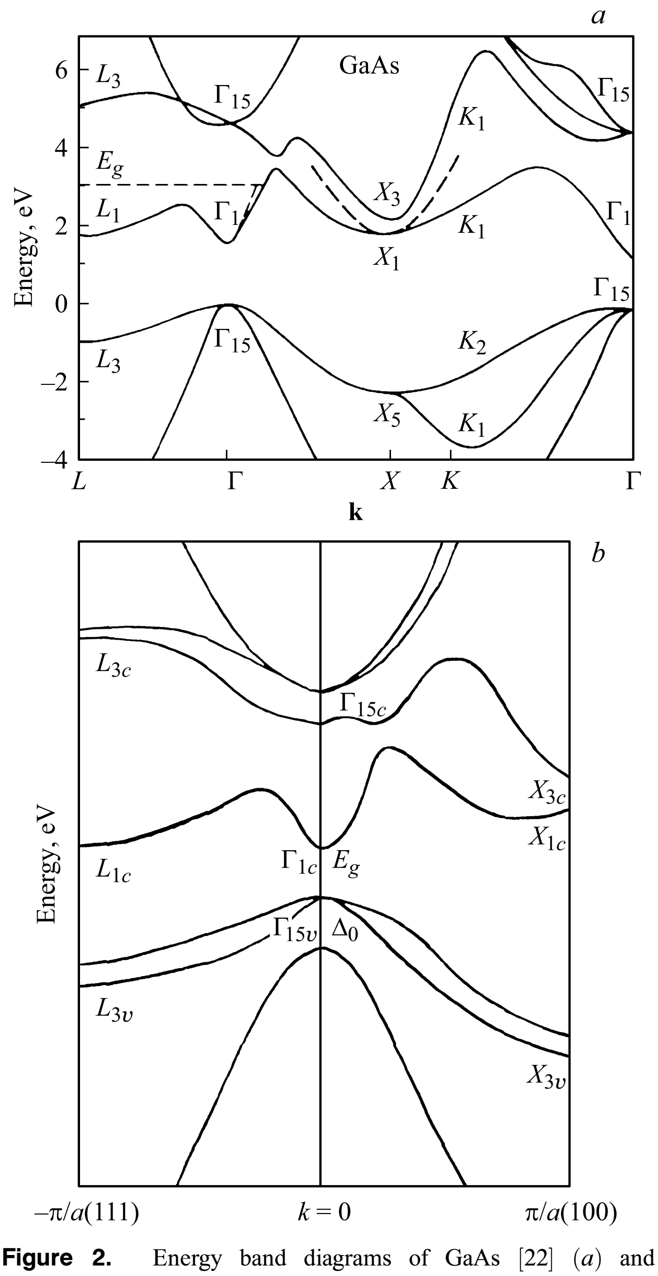


**Figure 2.** Energy band diagrams of GaAs [22] (*a*) and GaSb [23] (*b*).

In the majority of the $A^{III}B^{V}$ semiconductors and their solid solutions (GaAs, InP, InGaAs(P), etc.), the ionization coefficients of holes and electrons are close to each other, so the values of the parameter $k = \beta/\alpha$ stay within the range 2–4, in contrast, for example, to Si, wherein the impact ionization by electrons is predominant and $k \approx 0.01-0.02$. That is why many efforts have been made during the last decades to create and study semiconductor materials with the high ratio of the ionization coefficients. As it was shown in the result of the theoretical and experimental studies, the narrow-gap semiconductor materials InAs, GaSb and the solid solutions based thereon have the high ratio of the ionization coefficients of electrons and holes, thereby allowing creating APD for the mid-infrared range with the low level of excessive noise. It was enabled by establishing a relation between the processes of impact ionization in the high electric field and features of the band structure of the $A^{III}B^{V}$ semiconductors [6,9].

The method of calculation of the distribution function of the charge carriers for the polar semiconductors of the GaAs and InP type when heating in the high electric field at the high energies was developed in the papers of A.P. Dmitriev and I.N. Yassievich [5,6]. These calculations allowed predicting the anisotropy of the ionization coefficients of electrons in GaAs in dependence on the orientation of the electric field in the crystal [29] by taking into account an important role of constants of intervalley interaction Γ-, $X$- and $L$-valleys when heating the charge carriers. In the paper [6], it has obtained formulas relating characteristic fields of impact ionization by electrons with material parameters in the multi-valley semiconductors of the GaAs and InP type.

In very strong fields, the function of distribution of carriers is determined by diffusion heating of electrons in the „heavy“ $X$-valley with scattering on deformation optical phonons. This case is important for understanding the anisotropy of the field dependences of the ionization coefficients in the multi-valley semiconductors, such as GaAs, InP and their solid solutions [30,31].

The paper [29] was the first to show that in the multi-valley semiconductors of the GaAs and InP type, the coefficients of impact ionization of electrons $\alpha(E)$ are anisotropic and have a various character of the dependence for different directions of the electric field. When the field $\mathbf{E}$ is applied along the crystal-lattice direction (100) or (110), there is ballistic heating in the Γ-valley and the dependence of the $\ln\alpha \propto E_{01}/E$ type is true, where $E_{01} = 2.6 \cdot 10^6$ V/cm. If $\mathbf{E} \parallel (111)$ and the ballistic heating in the Γ-valley is impossible, then the distribution function is formed due to the scattering of electrons from the $X$-valley. Then, the ionization coefficient of electrons in the strong fields ($E > 3.6 \cdot 10^5$ V/cm) shall be governed by a quadratic relationship $\ln\alpha \propto (E_{02}/E)^2$, where $E_{02} = 9 \cdot 10^5$ V/cm, and the function of distribution becomes isotropic [2].

For the ballistic mode, the dependence of the ionization coefficient on the electric field strength is given by the relationship [9]

$$\alpha(E) = \alpha_{01} \exp[-(E_{01}/E)], \tag{14}$$

where the characteristic field $E_{01}$ is written as

$$E_{01} = [2m_X(\varepsilon_{ie} - \Delta_X)]^{3/2} \Xi_{\Gamma X}{}^2 (2\pi\rho e V \hbar^3 \omega_{\Gamma X})^{-1} \times \mathrm{cth}(\hbar\omega_{\Gamma X}/2k_B T), \tag{15}$$

$m_X$ — the effective mass of electron at the bottom of the $X$-valley, $\Delta_X$ — the energy distance between the bottom of the conductivity band and the bottom of the $X$-valley, $\Xi_{\Gamma X}$ — the constant of the intervalley interaction for the Γ- and $X$-valleys, $\rho$ — the density of the crystal, $e$ — the charge of electron, $\hbar$ — the Planck constant, $\omega_{\Gamma X}$ — the frequency of the intervalley phonon for Γ- and $X$-valleys, $k_B$ — the Boltzmann's constant.

The following dependence is true in the diffusion mode with isotropic scattering [9]

$$\alpha(E) = \alpha_{02} \exp[-(E_{02}/E)^2], \tag{16}$$

and the characteristic field $E_{02}$ is expressed as follows

$$E_{02} = (m_X \Xi_{XX})^2 [3(\varepsilon_{ie} - \Delta_X)/\hbar\omega_{XX}]^{1/2} (\pi\rho e \hbar^2)^{-1} \times \mathrm{cth}^{1/2}(\hbar\omega_{XX}/2k_B T), \tag{17}$$

where $\Xi_{XX}$ — the constant of the intervalley interaction between the equivalent valleys, $\omega_{XX}$ — the frequency of the respective intervalley phonon. At the same time, values of the coefficients of impact ionization for the field direction $\mathbf{E} \parallel (111)$ should be lower than in the directions (100) and (110).

The experimental measurements of the ionization coefficients of electrons in the high electric fields can be used to determine values of the characteristic fields $E_{01}$ and $E_{02}$, and, after that, by means of the formulas (15) and (17), to find the constants of the intervalley interaction $\Gamma-X$, $X-X$ and compare them with the calculated data [25–28,32]. Table 1 shows values of the characteristic fields $E_{01}$, $E_{02}$ and the constants of the intervalley interaction $\Xi_{\Gamma X}$, $\Xi_{XX}$ for the GaAs, InP, GaAlSb and GaAsSb semiconductor compounds. The experimental values of the ionization coefficients in GaAs for the orientations (100) and (111), as well as InP (100) were taken from the papers [28,32–34]. The values of the characteristic fields in the GaAlSb and GaAsSb solid solutions have been obtained from the experimentally measured coefficients of impact ionization [31]. As it follows from the table, there is evidently good agreement of the experimental results with the theoretical estimates [30].

For the first time the anisotropy of the ionization coefficient was proofed experimentally in [33] when studying the field dependences in the AlGaSb/GaAs system. Fig. 3 shows the dependence of the ionization coefficient of electrons

**Table 1.** Constants of the intervalley interaction, which are calculated based on the experimental values of the characteristic field $E_{01}$ and $E_{02}$ [28,31-34] by means of the expressions (15) and (17)

| Material | Orientation of the substrate | $E_{01}$, V/cm | $E_{02}$, V/cm | $\Xi_{\Gamma X}$, eV/cm | $\Xi_{XX}$, eV/cm |
|---|---|---|---|---|---|
| GaAs | (100) | $2.6 \cdot 10^6$ | | $1.4 \cdot 10^9$ | |
| | (111) | | $8 \cdot 10^5$ | | $1 \cdot 10^9$ |
| InP | (100) | $3 \cdot 10^6$ | | $1.2 \cdot 10^9$ | |
| $Ga_{1-x}Al_xSb$ | | | | | |
| $x = 0$ | (100) | $5.4 \cdot 10^5$ | $1.8 \cdot 10^9$ | | |
| $x = 0.05$ | (111) | | $1.3 \cdot 10^5$ | | $8.4 \cdot 10^8$ |
| $x = 0.07$ | (111) | | $1.75 \cdot 10^5$ | | $9.8 \cdot 10^8$ |
| $x = 0.15$ | (100) | $6.4 \cdot 10^5$ | | $1.4 \cdot 10^9$ | |
| $GaAs_{1-x}Sb_x$ | (100) | $5 \cdot 10^5$ | | $7.2 \cdot 10^8$ | |
| $x = 0.12$ | | | | | |

in GaAs on inverse strength of the electric field for the two orientations of the vector **E** along the directions (100) and (111). As it is clear from the figure, with change in the field strength the ratio of the ionization coefficients also noticeably changes, while the ionization coefficient of electrons along the field direction $\mathbf{E} \parallel (111)$ becomes less than for the direction (100). Note that the theoretical papers [35,36] devoted to the Monte-Carlo calculation of the coefficients of impact ionization in GaAs did not discover the anisotropy effect, as they used the simplest model of a semiconductor with a non-degenerate, spherically symmetrical band structure [37].

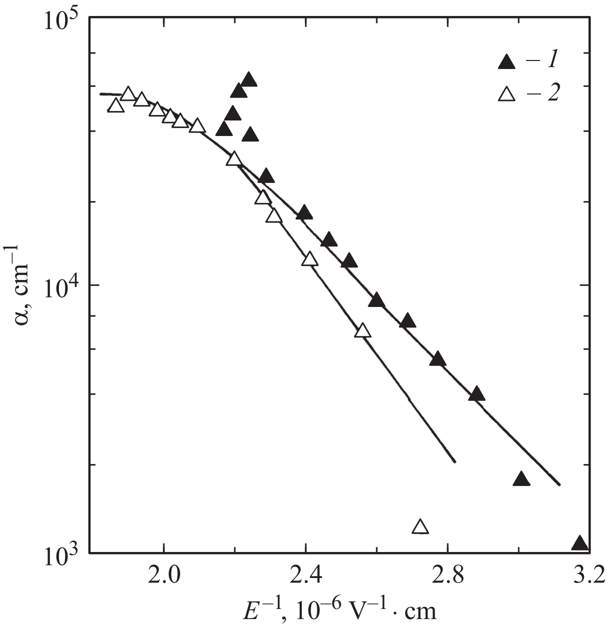


**Figure 3.** Anisotropy of the ionization coefficient of electrons in GaAs at the temperature of 300 K. Dots — the experimental data for the cases $\mathbf{E} \parallel (100)$ (*1*) and $\mathbf{E} \parallel (111)$ (*2*) [33], the solid curves — the calculation results [9].

The experimental results of the papers [33,34], were confirmed in the publications [29,37], as well as in the paper [31] when studying an orientation dependence of the ionization coefficients in the GaAlSb solid solutions. Later on, we observed the anisotropy of the ionization coefficients of holes and electrons in the GaSb-based structures when taking into account a role of the *L*- and *X*-valleys and when changing the orientation of the electric field along the directions (100) and (111).

The theoretical calculations of the distribution function of the charge carriers in the high electric field in the $A^{III}B^{V}$ semiconductors of the GaAs, GaSb and InP type can be used when analyzing the processes of impact ionization in other semiconductor compounds in order to choose promising materials for APD creation.

## 4. Impact ionization by holes in the semiconductors with a complex structure of the valence band

The paper [24] was the first to study a heating process for the charge carriers in the electric field in the semiconductor with two valence subbands with substantially different effective masses of the holes. Following the Gribnikov method, we have theoretically studied the processes of impact ionization of holes in the $A^{III}B^{V}$ semiconductors with the complex structure of the valence band [30]. In the majority of the semiconductors, the valence band includes bands of heavy and light holes, as well as the spin-orbit split-off band. In the materials with a various band gap and a different spin-orbit split-off value the three important cases can be realized: $E_g \gg \Delta$ (Ge, GaAs, InP), $E_g \ll \Delta$ (InSb), $E_g \approx \Delta$ (InAs, GaSb), where $\Delta$ — a value of the spin-orbit splitting of the valence band. As it was demonstrated by the calculation, in the first two cases the main role in the formation of the distribution function at the high energy values is played by the scattering on deformation optical phonons and the ionization coefficients of holes in these semiconductors are expressed as

$$\beta(E) = \beta_{01} \exp[-(E_{01}/E)], \tag{18}$$

where the value of the characteristic field $E_{01}$ depends on parameters of the band structure, the constant of the deformation potential and the temperature [6].

The valence bands of the studied semiconductors are arranged in a similar way. The spectrum of heavy holes is close to a parabolic one and characterized by the effective mass $m_h$, whose values are approximately the same for all the $\mathrm{A^{III}B^{V}}$ semiconductors, as the effective masses of electrons differ strongly [38,39]. At low energies, the mass of light holes is much less than the mass of heavy holes ($m_l \ll m_h$). With increase in the energy, the mass of light holes increases and at the energy $\varepsilon \geq \Delta$ it becomes comparable with the mass of heavy holes ($m_l \approx m_h$). At the same time, the mass of holes in the spin-orbit split-off band always meets the condition $m_{so} \ll m_h$. Due to similarity of the band structures in the semiconductors of the GaAs, InP type, the scattering on the deformation optical oscillations in them is of the same order of value.

At the same time, the process of impact ionization in InSb has a number of differences [40]. In this material, the band gap is substantially lower than the spin-orbit splitting of the valence band: $E_g = 0.17$ eV, $\Delta = 0.8$ eV at $T = 300$ K [38,41]. The main mechanism of electron scattering within the InSb conductivity band is scattering on longitudinal optical phonons. The calculation of characteristic field $E_{01}$ gives a value of $\sim 10^3$ V/cm [42,43]. But, in the valence band in InSb, as well as in GaAs, there is strong scattering on the deformation optical phonons, thereby resulting in increase in the characteristic field $E_{01}$ and, therefore, to the sharp decrease in the ionization coefficient of holes $\beta(E)$. This coefficient also reduces due to the fact that the ballistic heating involves only light holes making up a small portion of the total number of the holes, as their effective mass is much smaller than the mass of the heavy holes ($m_l = 0.015\,m_0$, $m_h = 0.43\,m_0$). At the same time, the effective heating in the conductivity band is contributed by all the electrons with the threshold energy of ionization $\varepsilon_{ie} \approx E_g$ [40]. That is why hole multiplication was not observed in the experiments on impact ionization in InSb [44–46].

## 5. Coefficient of impact ionization of holes in the semiconductors with „resonance" of the bands $E_g \approx \Delta$ (InAs, GaSb)

The most interesting situation in the semiconductors of the InAs, GaSb type (see Fig. 4 and 2, $b$) and their solid solutions, in which the relationship $E_g \approx \Delta$ is fulfilled — the so-called „resonance" of the bands. This effect plays an important role when creating the avalanche photodiodes

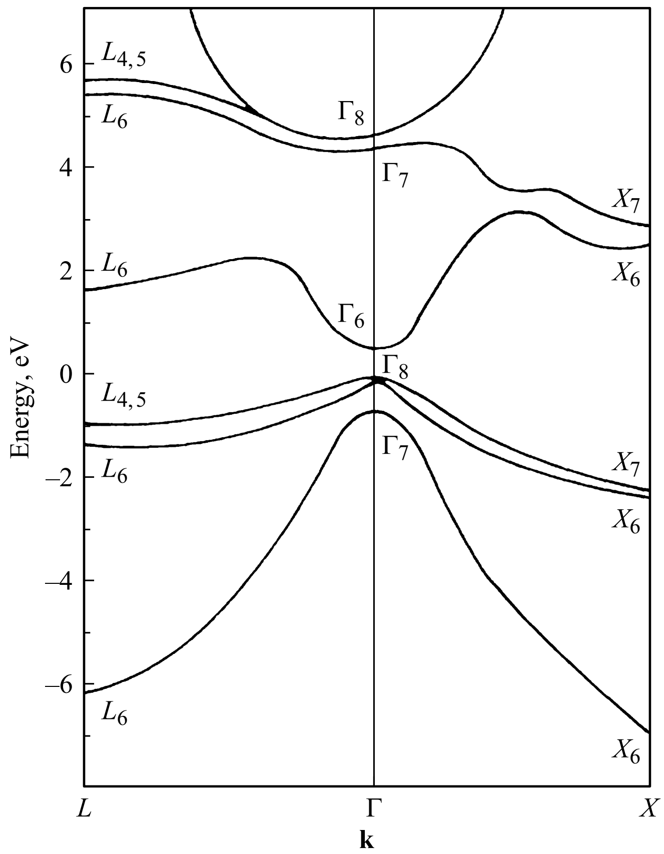


**Figure 4.** Energy band diagram of InAs [23].

with the high ratio of the ionization coefficients of electrons and holes [16], especially those based on the narrow-gap semiconductors.

The avalanche multiplication in the $p-n$-photodiodes based on InAs at the room temperature was discovered for the first time in the paper [47]. Under the helium-neon laser's illumination (the wavelength 0.633 $\mu$m, the modulation frequency 125 MHz) the multiplication coefficient $M \approx 1.1-12.5$ was measured in dependence on the value of the reverse bias within the range 0.5–10 V.

The first experimental data on the avalanche multiplication in the InAs diffusion $p-n$-junctions were obtained in Ioffe Institute in 1967 (see Fig. 5) [48]. That paper provides the first proof of the asymmetry of the multiplication coefficient of holes and electrons, when the photodiode $n-p$-structure is affected by the monochromatic short-wave radiation with the wavelength $\lambda = 1.5\,\mu$m (heavily absorbed within the $n$-region), and by the long-wave radiation ($\lambda = 3.8$ and $3.95\,\mu$m) (absorbed within the $p$-region). With the reverse bias $U = 2-10$ V, the multiplication coefficient of electrons $M_e$ was changing from 7 to 12 and was much less than the multiplication coefficient of holes $M_h$, which was 40–60. The same paper was the first to evaluate the threshold energy of electron ionization by comparison of the experimental data with calculation curves of the paper [3]. The estimates have shown that the threshold

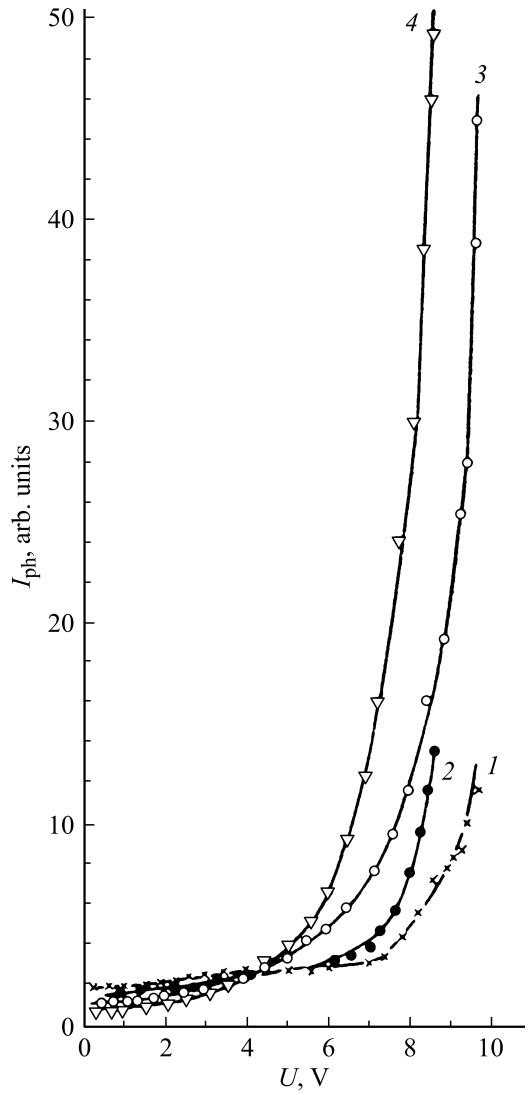


**Figure 5.** Dependences of the photocurrent value on the reverse bias for the two InAs $p-n$-junction (*1, 3* — the sample 39; *2, 4* — the sample 34), illuminated at the $p$-side by radiation with the wavelength, $\mu$m: *1, 2* — 1.5; *3* — 3.8; *4* — 3.95 [48].

energy for electron ionization is within $1.2E_g \le \varepsilon_{ie} \le 1.6E_g$ (where $E_g = 0.42$ eV) at the value of the electric field $E_m = 2 \cdot (10^4 - 10^5)$ V/cm.

The threshold energy of hole ionization in several photodiode $p-n$-structures, illuminated at the $p$- or $n$-sides, was determined by experimental investigation of the minimum energy required to start the avalanche multiplication by holes [49]. It turned out that the ionization thresholds of electrons and holes are close to each other and stay within the range 0.4–0.5 eV. As the threshold energy for ionization by heavy holes was $\varepsilon_{ih} \approx 2E_g = 0.84$ eV, it was supposed that the direct impact ionization in InAs was realized by involvement of holes from the spin-orbit split-off band, whose effective mass $m_{so}$ was smaller than the mass of heavy holes ($m_{so} = 0.16\,m_0$, $m_h = 0.41\,m_0$), and the energy was close to the band gap ($\Delta \approx E_g$).

The papers [50,51] were the first to evaluate probabilities of various channels of impact ionization and Auger-recombination in InAs, which are realized with involvement of various subbands of the valence band, including the spin-orbit split-off band. The theoretical analysis demonstrated that in this case the Coulomb interaction of the charge carriers participating in the impact ionization is occurring at small transfer of the momentum, thereby substantially increasing the process probability. That is why in the materials, whose band gap is close to the value of the spin-orbit splitting (InAs, GaSb, HgCdTe and their solid solutions), the coefficient of impact ionization of holes is sharply increasing in comparison with the ionization coefficient of electrons. Fig. 6, *a* illustrates the experimental values of the ratio of the ionization coefficients of electrons and holes in InAs and the InAsSb, InGaAs, InAsSbP solid solutions in dependence on the composition [52]. Almost

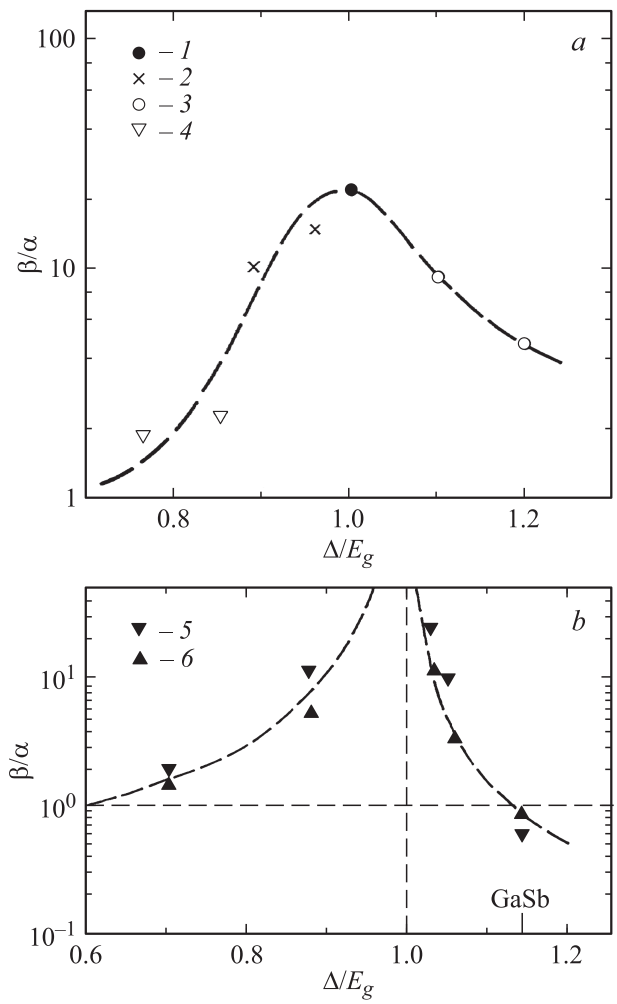


**Figure 6.** Ratio of the ionization coefficients of holes and electrons in dependence on the parameter $\Delta/E_g$ in the $A^{III}B^{V}$ semiconductors. *a* — data for InAs (*1*), $In_{1-x}Ga_xAs$ ($x = 0.02$, 0.04) (*2*), $InAs_{1-x}Sb_x$ ($x = 0.06$, 0.08) (*3*), InAsSbP (*4*) [52]. *b* — data for $Ga_{1-x}Al_xSb$ at the strengths of the electric field $E = 3.3 \cdot 10^4$ (*5*) and $4 \cdot 10^4$ V/cm (*6*) [53].

at the same time, the „resonance" impact ionization by holes was observed by various authors in GaAlSb (see Fig. 6, *b*) [53–56], as well as in the zero-gap semiconductors in the HgCdTe system [57]. Later on, the effect of the „resonance" impact ionization had been actively used by foreign authors to create APD with the high ratio of the coefficient of impact ionization [14].

The effects of avalanche multiplication and the field dependence of the ionization coefficients in the $p-n$-junctions based on InAs and its solid solutions such as InGaAs, InAsSb at the temperatures 77 and 300 K were investigated in detail in the papers [49,58,59]. The diffusion and epitaxial structures were grown on the *n*-InAs substrates.

Fig. 7 shows the field dependences of the ionization coefficients of holes and electrons at $T = 77$ K for the $p-n$-structure on InAs. It was established that within the whole studied range of strengths of the electric field the ionization coefficient of holes exceeded the ionization coefficient of electrons by more than an order. A typical „break" on the dependence $\beta(1/E)$ seems to be caused by a change of the mechanism of impact ionization by holes when increasing the strength of the electric field. In weak fields, this process is contributed by the holes of the spin-orbit split-off band, whose ionization threshold is close to the threshold of the electron ($\varepsilon_{ih} \approx \Delta \approx E_g = 0.73$ eV). The increase in the ionization coefficient of holes with increase in the field strength $E$ may be associated with the contribution of the heavy holes, whose ionization threshold is equal to $\varepsilon_{ih} \approx 2E_g = 0.82$ eV.

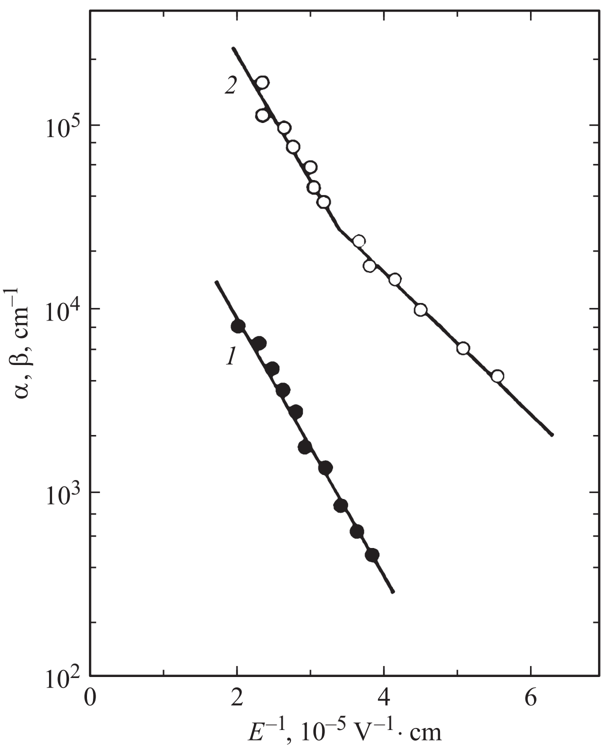


**Figure 7.** Dependences of the ionization coefficients for electrons (*1*) and holes (*2*) on the reverse strength of the electric field in the $p-n$-junctions based on InAs at the temperature of 77 K [58].

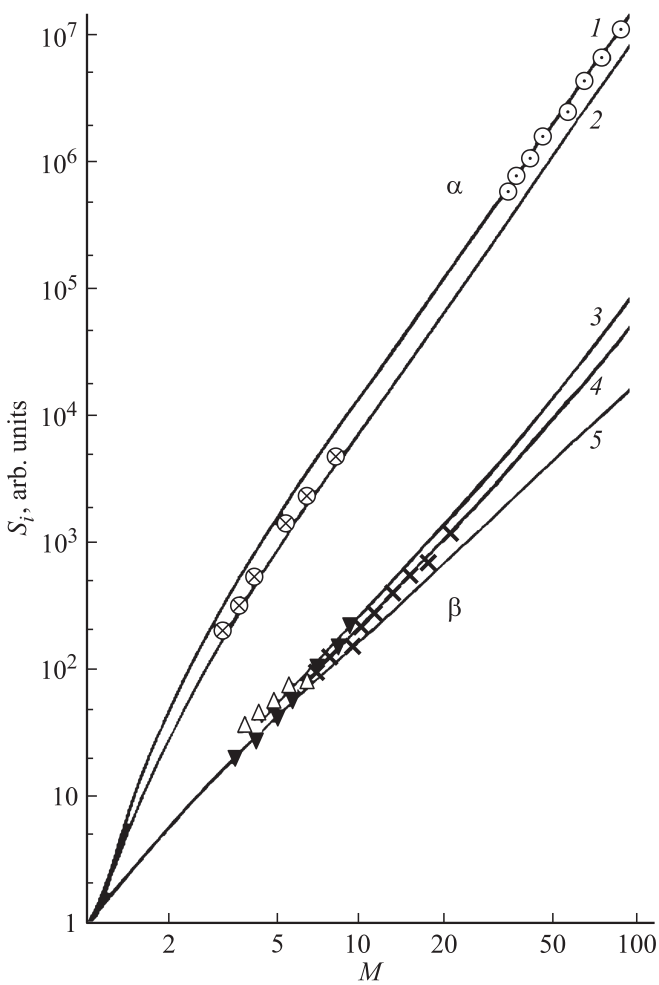


**Figure 8.** Dependences of the noise spectral density $S_i$ on the multiplication coefficient for InAs and InGaAs APD structures in case of electron ($\alpha$) and hole ($\beta$) injection for the various values $k = \beta/\alpha$. Dots — the experimental data [49], the curves — the calculation results for $k = 10$ (*1, 3*), 20 (*2, 4*), $\infty$ (*5*) [12].

The excessive noise in the InAs- and InGaAs-based APDs in the spectral range $3-5\,\mu$m was investigated in the paper [49]. Fig. 8 shows the dependence of the noise spectral density on the multiplication coefficient for the studied structures. The experimental ratio of the ionization coefficients $\beta/\alpha$ was up to 20–50. Due to predominant contribution of the holes from the spin-orbit split-off band, a minimum value of the noise factor $F(M) = M^{0.1}$ was obtained, which corresponds to practically monopolarity multiplication of charge carriers.

One question is interesting — how the threshold energies of impact ionization are changing in the solid solutions with change of the band structure of the material. Specifically, when designing APDs based on the InGaAs, GaAsSb solid solutions [59,60], which are more narrow-gap semiconductors in comparison with GaAs, it shall take into account that the threshold of direct ionization is reduced by adding a material with a higher or lower value of the ionization coefficient of holes and electrons and stays within the first conductivity band due to a smaller value of the effective mass of electrons in comparison with the mass of the holes. This threshold is closer to the band gap ($\varepsilon_{ie} \approx E_g$). That is why the condition $\alpha > \beta$ is always fulfilled in these materials. For example, in the InGaAs solid solution with a high content of GaAs the subsidiary $X$-valley is highly located in energy band diagram so the scattering to this valley can be neglected. Therefore, the ionization coefficient of electrons in this material should be higher than in GaAs.

It should be noted that in the InAs solid solutions (InAsSb, InAsSbP, etc.), with the change of the composition and the temperature, there is also a change of the relationship between the band gap and the value of the spin-orbit splitting, thereby, in turn, changing the ratio of the ionization coefficients by deviation from the band resonance when adding another material. Specifically, as in GaAs and InAsSb $\alpha > \beta$, then the InGaAs solid solution will have the lower ionization coefficient of holes in comparison with InAs (see Fig. 6, $a$) [52].

Above, we have considered the orientation anisotropy of the electron ionization coefficient in the GaAs and InP multi-valley semiconductors. Let us now consider how the ratio of the ionization coefficients of holes and electrons $k = \beta/\alpha$ is changing in GaSb due to the subsidiary valleys in this material. The GaSb band structure has the $X$- and $L$-valleys with the high effective mass of electrons. At the same time, the fourfold degenerate subsidiary $L$-valley is located below the minimum of the central $\Gamma$-valley along the direction (111) by the value $\Delta_L = 0.08\,\text{eV}$, whereas for the $X$-valley the gap is $\Delta_X = 0.5\,\text{eV}$ (see Fig. 2, $b$). As the effective mass of electrons in the $L$-valley is much higher than the effective mass in the $\Gamma$-minimum ($m_L = 0.5\,m_0$, $m_\Gamma = 0.043\,m_0$, respectively), then a significant number of electrons will be in the $L$-valley already at the room temperature [9]. In the electric field, the average energy of electrons, which is characterized by the electron temperature $T_e$, increases with increase in the electric field strength, thereby resulting in the most part of electrons is situated in the $L$-valley. The estimation show that the ratio of the electron concentrations in the $\Gamma$- and $L$-valleys expressed as

$$n_\Gamma/n_L = [\rho_\Gamma(\varepsilon)/\rho_L(\varepsilon)]\exp(\Delta_L/T_e). \qquad (19)$$

In the fourfold degenerate $L$-valley, the densities of the states are correlated as effective masses with a power exponent of 3/2 and we obtain

$$n_\Gamma/n_L = (m_\Gamma/m_L)^{3/2}\exp(\Delta_L/T_e), \qquad (20)$$

so the number of electrons, which can participate in impact ionization, is only a small portion of their total quantity:

$$n_\Gamma = n/[1 + 4(m_\Gamma + m_L)^{3/2}\exp(-\Delta_L/T_e)] \approx 0.017, \quad (21)$$

where $\Delta_L = 0.08\,\text{eV}$, $T_e = 3\hbar\omega_0$, $\hbar\omega_0 = 0.029\,\text{eV}$. As the impact ionization involves only the electrons of the $\Gamma$-valley with energies equal to or higher than the threshold energy, then the number of these electrons with the small effective mass ($m_\Gamma = 0.023\,m_0$) is determined by the threshold value and the total number of the particles in the $\Gamma$-valley. As a result, GaSb and the solid solutions with compositions close thereto will have conditions, when the ionization coefficient of electrons is substantially reduced in comparison with other semiconductor materials due to strong reduction of a pre-exponential factor in the formula $\alpha(E) = \alpha_{01}\exp[-(E_{01}/E)]$, — for example, in GaAlSb, GaInSb, etc. If the electric field in the structure is directed along the axis (100), when the role of the $L$-valley is not important, then the big ratio of the ionization coefficients $\beta/\alpha$ can be achieved by means of increasing the ionization coefficient of holes due to the resonance ionization ($\Delta \approx E_g$). The GaSb was the first one to have fortunate combination of two factors discovered: a low-lying heavy $L$-valley that pumping out the electrons from the $X$-valley, and, at the same time, the band „resonance“ phenomenon with involvement of holes from the spin-orbit split-off band with the low ionization threshold. Thus in the GaSb and in the solid solutions with compositions close thereto the monopolarity multiplication by holes can be realized thereby allowing to create practically „noiseless“ avalanche photodiodes.

## 6. Monopolarity multiplication of the charge carriers in structures with separated regions of absorption and multiplication

In order to reduce the excessive noise and increase the ratio of the ionization coefficients, the separate absorption and multiplication avalanche photodiodes (SAM APDs) have been developed for the mid-infrared region of the spectrum. The localization of the absorption region in the narrow-gap semiconductor and the multiplication region in the wide-band material allows reducing a value of the electric field at the heterointerface of the narrow-gap region and avoiding increase in tunnel current, when the avalanche is developing within the wide-band region. This APD design was suggested for the first time in a paper of Japanese authors of the NTT Corp. [61] to be based on the $In_{0.53}Ga_{0.47}As/InP$ structure, which was grown by the liquid-phase epitaxy (LPE) on the $p^+$-InP (100) substrate for the spectral range $1-1.6\,\mu$m. The absorption region was in the narrow-gap InGaAs solid solution, while the multiplication region was in the wide-band InP layer. The suggested structure allowed reducing the diffusion current and decreasing the electron tunneling probability at the heterointerface out of the InP valence band to the InGaAs conductivity band [62]. It was shown that the ionization coefficient of holes exceeded the ionization coefficient of electrons in 2–4 times, while the noise level was lower than that of the germanium APD under irradiation by the pulses of the YAG : Nd-laser.

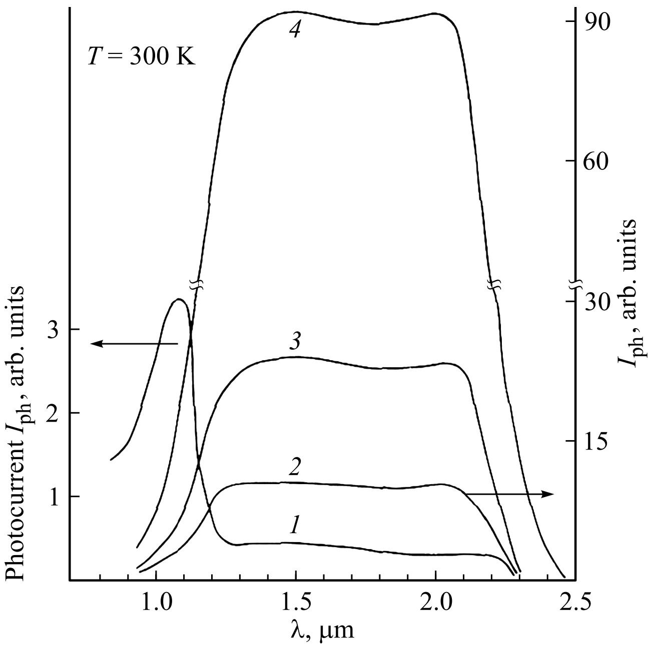


**Figure 9.** Photocurrent spectra at the room temperature for the GaInAsSb/GaAlAsSb SAM APD in dependence on the reverse bias, V: *1* — 0, *2* — 5, *3* — 10, *4* — 20 [63].

In order to create low-noise, high-speed APDs designed to operate within the mid-infrared range $2-5\,\mu$m, we have grown a structure based on the GaInAsSb/GaAlAsSb solid solutions [63]. It should be underlined that this APDs have been designed with predominantly multiplication by holes in the $n$-$GaAl_{0.04}AsSb_{0.96}$ absorption layer, wherein the „resonance“ composition for holes was implemented ($E_g \approx \Delta \approx 0.76\,\text{eV}$). This structure was the first to observe the monopolarity multiplication of holes from the spin-orbit split-off band for the (111) orientation of the electric field and to obtain the lowest noise factor of $F(M) = 1.6$ at the ratio of the ionization coefficients $k = \beta/\alpha \approx 6-10$ [64]. The $In_{0.22}Ga_{0.78}As_{0.18}Sb_{0.72}$ narrow-gap absorption region ($E_g = 0.54\,\text{eV}$ at $T = 77\,\text{K}$) has been grown by the liquid-phase epitaxy on the $n$-GaSb:Te (111) substrate using Pb [65]. The concentration of the carriers in the narrow-gap region was low and equal to $n = (2-5) \cdot 10^{15}\,\text{cm}^{-3}$ [66]. Within the multiplication region, the $p^+-N$-junction was in an indirect-band alloy close in terms of the composition to GaSb, $n$-$Ga_{0.66}Al_{0.34}As_{0.025}Sb_{0.975}$ ($E_g = 1.2\,\text{eV}$) with the concentration of the carriers in the $p^+$-layer equal to $5 \cdot 10^{18}\,\text{cm}^{-3}$. The breakdown voltage was determined by a wide-band material to be $U_B = 21-24\,\text{V}$ at the temperature $T = 296\,\text{K}$ and $18-20\,\text{V}$ at 77 K. The electric field strength was equal to $E = 3.5 \cdot 10^5\,\text{V/cm}$. The significant multiplication was already observed at $U_B > 6\,\text{V}$. The maximum value of the multiplication coefficient varied from $M = 20-30$ at the room temperature to $M = 100-400$ at $T = 78\,\text{K}$. When illuminating by monochromatic radiation with the wavelength of $\lambda = 1.5-2.1\,\mu$m through the $p^+$-GaSb covering layer, the multiplication coefficient increased with increase in the wavelength. The space charge region was in the narrow-gap GaAl(As)Sb absorption region near the interface of the $p^+-N$-junction provided that the impact ionization is implemented by the carriers with a higher coefficient of impact ionization. The spectral characteristic of the studied SAM APD is shown on Fig. 9 [63] at the reverse bias within the range from zero to $-20\,\text{V}$.

The spectral density of the noise power of the avalanche multiplication is shown on Fig. 10, $a$ in dependence on the value of the photocurrent $S_i(I_{ph})$ for the $n$-GaSb/$n$-GaInAsSb/$p$-GaAlAsSb heterostructure. This dependence was experimentally determined by means of a

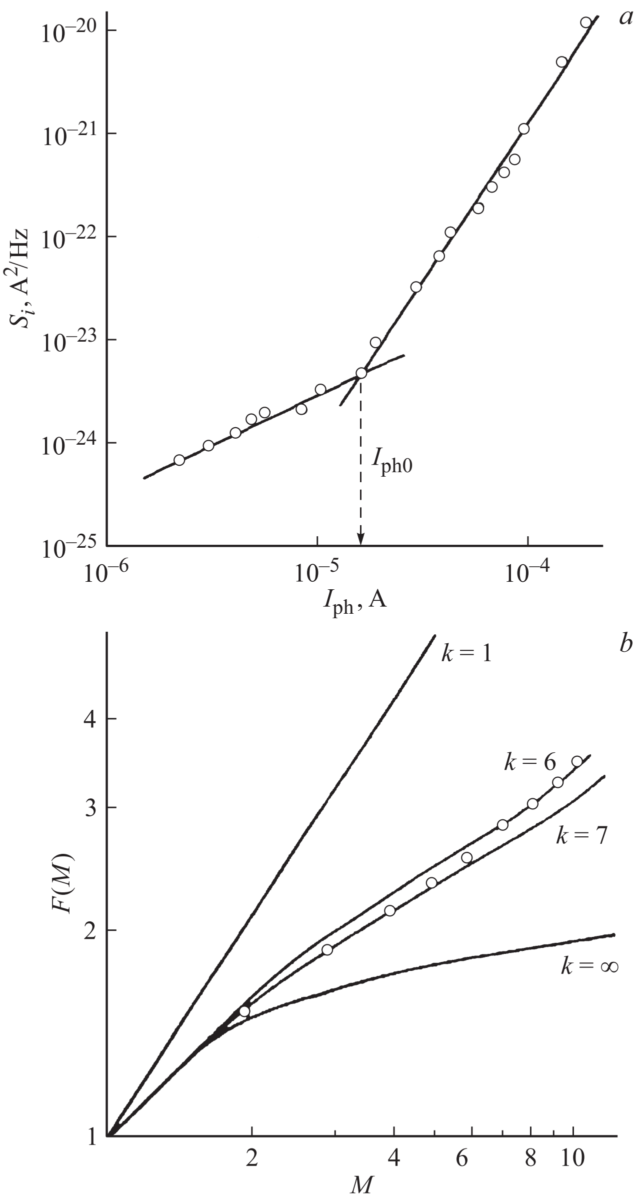


**Figure 10.** Dependences of the spectral density of noise power on the photocurrent ($a$), and dependences of the excessive noise factor on the multiplication coefficient ($b$) for the GaSb/GaInAsSb/GaAlAsSb APDs. Dots — the experimental data [64], the curves ($b$) — the calculation results for different values $k = \beta/\alpha$ [12].

**Table 2.** Parameters of the three types of APD based on the GaInAsSb/AlGa(As)Sb heterostructure, which differ in a design of the structure and a composition of the absorption and multiplication regions [63]

| APD | | $y$ $(F \sim M^y)$ | $F(M = 10)$ | $\beta/\alpha$ |
|---|---|---|---|---|
| Absorption region | Multiplication region | | | |
| $In_{0.22}Ga_{0.78}As_{0.18}Sb_{0.82}$ | $n$-$In_{0.22}Ga_{0.78}As_{0.18}Sb_{0.82}$ $p$-$Al_{0.34}Ga_{0.66}As_{0.014}Sb_{0.986}$ | 0.5 | 3.2 | 7 |
| $In_{0.22}Ga_{0.78}As_{0.18}Sb_{0.82}$ | $n{-}p$-$Al_{0.34}Ga_{0.66}As_{0.014}Sb_{0.986}$ | 0.7 | 5.0 | 3 |
| $In_{0.22}Ga_{0.78}As_{0.18}Sb_{0.82}$ | $n$-$Ga_{0.96}Al_{0.04}Sb$/$p$-$Al_{0.34}Ga_{0.66}As_{0.014}Sb_{0.986}$ | 0.2 | 1.6 | 60 |

noise generator at the frequency of $f = 3$ MHz within the frequency band $\Delta f = 0.3$ MHz [64,67]. The measurements were carried out when the studied structure was affected by radiation of the semiconductor laser with the wavelength of $\lambda = 2\,\mu$m and without the irradiation. In doing so, no correlation was supposed to be between noises of the dark current and the photocurrent. In general, the spectral noise density was determined by the formula (10). The experimentally obtained dependence $S_i(I_{\text{ph}})$ was well expressed as

$$S_i = 2eI_{\text{ph}0}M^y, \tag{22}$$

where $M = I_{\text{ph}}/I_{\text{ph}0}$, while the value of the avalanche-initiating photocurrent ($I_{\text{ph}0}$) was determined by a point of „break“ of the dependence.

Fig. 10, *b* shows the calculated dependences of the excessive noise coefficient on the multiplication coefficient $F(M)$ for various values of the ratio of the ionization coefficients $k = \beta/\alpha$ from the paper [12]. In the same figure the experimental data for the APD samples based on the GaInAsSb/AlGa(As)Sb heterostructure from the paper [64] are represented by the open circles. The best agreement of the theoretical and experimental results is achieved at $k \approx 6{-}7$. The noise coefficient value in the $p{-}N$-structure of GaInAsSb/AlGa(As)Sb was $F(M) = 3.2$ at $M = 10$.

Table 2 shows data which characterize the absorption and multiplication regions, the value of the excessive noise factor, as well as the ratio of the ionization coefficients for the three types of APDs based on the GaInAsSb/AlGa(As)Sb structure grown and studied by us. It is clear that the lowest noise factor ($F = 1.6$) was achieved in the separate absorption and multiplication avalanche photodiodes. For comparison, Table 3 shows the values of the ratio of the ionization coefficients and the noise factor for a number of APDs based on various materials as per reference data.

The studied effect of practically monopolarity multiplication of charge carriers allows increasing the generation rate of the electron-hole pairs by hot charge carriers, too. In the narrow-gap solid solution, the drift time of the carriers through the space charge region ($\tau_i$) is expressed as [12,71]

$$1/\tau_i = \beta(E)V_{\text{dr}}(E), \tag{23}$$

where $V_{\text{dr}}$ — the drift velocity of the holes at the field $E = 2 \cdot 10^4$ V/cm. Hence, using the experimentally measured value of the ionization coefficient of holes $\beta(E) = 2 \cdot 10^4\,\text{cm}^{-1}$ [64] and $V_{\text{dr}} \sim 5 \cdot 10^6$ cm/s, we find a quite reasonable value $1/\tau_i \sim 10^{11}\,\text{s}^{-1}$.

**Table 3.** Ratio of the ionization coefficients $k = \beta/\alpha$ and the excessive noise factor $F(M)$ for the avalanche photodiodes based on the various semiconductor compounds at the room temperature and at 77 K (specified)

| Material | $k=\beta/\alpha$ | $F(M=10)$ | References |
|---|---|---|---|
| $Ga_{0.47}In_{0.53}As$/InP (100) | 2–3 | 3.3 | [17,67] |
| InGaAsP/InP (100) | 0.3 | 3.5 | [17,68] |
| GaAlAs/GaAs (100) | 1 | 5.9 | [8,18,69] |
| $Ga_{0.72}Al_{0.28}Sb$/GaSb (100) | 2 | 5 | [53] |
| $Ga_{0.05}Al_{0.95}Sb$/GaSb (111) | 16 | 1.2 | [55] |
| GaSb (111) | 100 | 1.9 ($T=77$ K) | [17] |
| InAs | 20–50 | 1.1 ($T=77$ K) | [49] |
| Ge | 2 | 7 | [70] |
| Si (111) | 0.02 | 5 ($M=100$) | [70] |

Previously, we had obtained data of measurement of the excessive noise factor in APD based on the solid solutions of another composition, which is different from the „resonance“ one. The avalanche multiplication and the field dependences of the ionization coefficients were studied in the structure based on the $Ga_{0.8}In_{0.2}As_{0.17}Sb_{0.83}$ solid solution also grown on the GaSb substrate with the (111) orientation [16]. This structure has the value of the spin-orbit splitting somewhat shifted from the „resonance“ value, but the holes still contribute a lot to the process of impact ionization. Furthermore, the band structure in the (111) direction was also modified: in this solid solution the $L$-valley is located above the minimum of the $\Gamma$-valley by the value $\Delta_L \geq 0.7$ eV, which exceeds the threshold energy of electrons $\varepsilon_{ie} \approx 0.62$ eV. At the same time, there is no scattering of the „heavy“ electrons into the $L$-valley. That is why for APD based on this solid solution there was a lower value of the ionization coefficient of holes and a somewhat higher value of the ionization coefficient of electrons in comparison with GaSb (in the studied solid solution $\alpha \geq 10^4\,\text{cm}^{-1}$, whereas in GaSb $\alpha \sim 10^3\,\text{cm}^{-1}$ in the same electric field). As a result, the value of the noise factor as found from the experimental data was $F(M) = 3.2$ at $M = 10$.

Note that in recent studies of foreign researchers, which are devoted to low-noise APDs based on the AlInAsSb/GaSb and AlGaAs/GaAs heterostructures for the spectral range $1-1.3\,\mu$m [72–74], the ratio of the ionization coefficients of electrons and holes $k = \beta/\alpha$, as well as the field dependences of the parameters $\alpha$ and $\beta$ were calculated by the Monte-Carlo method without taking into account a real band structure of the materials, but using the experimental data for the $p-n$-homojunctions [72]. This approach results in clearly overestimated results in comparison with silicon APDs.

## 7. Sensitivity threshold of the optoelectronic receiving module with the avalanche photodiode based on GaInAsSb/GaAl(As)Sb with separated regions of absorption and multiplication

The threshold sensitivity of the receiving optoelectronic modules for high-speed FOCLs, which apply the $p-i-n$-APDs for the near-infrared range $1.3-1.55\,\mu$m based on the GaInAs/InP and germanium semiconductor compounds has been studied in the paper [75]. Advancing to the mid-infrared range is important to improve the sensitivity of the receiving modules and to increase the distance between the transponders. The high threshold sensitivity of this module can be achieved only by the big asymmetry of the ionization coefficients of the charge carriers in the APD used. The formula for calculation of the minimum power detected by the digital receiving module was deduced in [76]:

$$\eta\langle P_{\text{APD}}\rangle = A\big[(\langle i_a^2\rangle)^{1/2}/M + eQF(M)I_1B\big], \qquad (24)$$

where $\eta$ — the efficiency of transforming the incident optical power $P$ to the electrical signal current, which takes into account the quantum efficiency of the detector, $A = Q/(hc/e\lambda)$, $h$ — the Planck constant, $c$ — the speed of light, $\langle i_a^2\rangle$ — the average value of a squared noise current of the detector and the receiver, $I_1$ — the Personic integral, whose value is 0.5 for rectangular pulses, $B$ — bit rate, $Q$ — the dimensionless parameter determining the probability of error in the digital signal (bit error rate, BER). In particular, the error probability $\text{BER} = 10^{-9}$ corresponds to the value $Q = 6$.

As the excessive noise factor $F(M)$ is a rising function of the average value of the multiplication coefficient $\langle M\rangle$, the optical signal power required to obtain the receiver sensitivity equal to $\eta\langle P_{\text{APD}}\rangle$, decreases proportionally to $\langle M\rangle$, provided that this value is small. At the same time, a noticeable increase in the multiplication coefficient $M$ results in increase in the noise factor $F(M)$, thereby increasing the second term in the formula (24), so it becomes a dominant one. As a result, the quantum efficiency $\eta\langle P_{\text{APD}}\rangle$ starts rising. That is why there is an optimal value of the multiplication value $M_{\text{opt}}$, at which the value of the recorded power $\eta\langle P_{\text{APD}}\rangle$ is the smallest, which corresponds to the maximum sensitivity for this value of the ratio of the coefficients of impact ionization $k = \beta/\alpha$ and the noise current of a preamplifier.

The minimum sensitivity of the receiving optoelectronic module with the GaInAsSb/GaAl(As)Sb-based SAM SPD was calculated and experimentally determined by us under effect of radiation of the solid-state lasers which generate in the spectral range $2.06-2.09\,\mu$m [63,77].

Using the formula (24), we have calculated the dependence of the threshold optical power on the multiplication coefficient for our APD based on a GaInAsSb/GaAl(As)Sb structure with separate absorption and multiplication regions, which was grown on the GaSb (111) substrate, under the influence of the monochromatic radiation with the wavelength $\lambda = 2.1\,\mu$m. The obtained result was compared with the threshold sensitivity of the standard germanium APD under the effect of radiation with the wavelength of $1.5\,\mu$m. These data are shown in Fig. 11. The calculations were carried out to suppose that the ADP is connected to a transimpedance preamplifier, which is characterized by the following parameters: the transmission coefficient $g_T = 40\,$mS, the total input capacitance $C_T = 1.5\,$pF, the feedback resistance $R_{FB} = 750\,$kOhm, the data rate $B = 500\,$Mb/s. In doing so, for SAM APD based on the GaInAsSb/GaAl(As)Sb heterostructure a diameter of the sensitive area was equal to $200\,\mu$m, while the value of the $I-W$ sensitivity in the maximum of the spectral characteristic at the wavelength $2.1\,\mu$m was 1.1 A/W. Note that for SAM APD the calculation used the value $k = \beta/\alpha = 60$ (the case of predominant ionization by holes), and for the Ge-APD it was supposed that $k = \beta/\alpha = 2$ [70]. As a result, the receiving module based on SAM APD had a minimum calculated level of the detected power $\eta\langle P_{\text{APD}}\rangle = -43.2\,$dBm at $M_{\text{opt}} = 34-39$. As it is clear from Fig. 11, this value is close to the minimum value of sensitivity for the Ge-photodiode, which is $-41.8\,$dBm at $M_{\text{opt}} = 10$. Thus, the SAM APD developed in Ioffe Institute has a higher ratio of the ionization coefficients and significantly lower values of the spectral noise density than the germanium APD [63].

Our optoelectronic receiving module with SAM APD was tested by irradiation of the YLF:Ho ($\lambda = 2.06\,\mu$m) and YAG-Cr,Tm:Ho solid-state lasers ($\lambda = 2.09\,\mu$m) with the pulse duration of 10 ns [77]. Taking into account spectral and noise characteristics for the receiving optoelectronic module with SAM APD based on the GaInAsSb/GaAl(As)Sb heterostructure, we have obtained the threshold energy of the laser pulse $E = 6.2 \cdot 10^{-16}\,$J

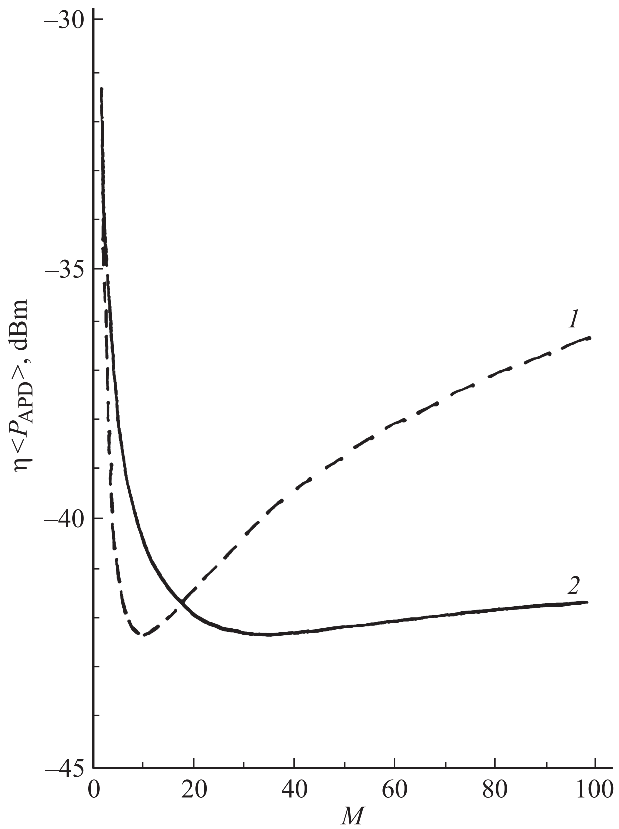


**Figure 11.** Dependences of the minimum detected power on the multiplication coefficient for the optoelectronic receiving module with two different APDs: *1* — Ge-APD ($\lambda = 1.55\,\mu$m) [70], *2* — SAM APD based on the GaInAsSb/GaAl(As)Sb heterostructure ($\lambda = 2.1\,\mu$m) [63].

($\lambda = 2.06-2.09\,\mu$m). For the receiving module with the Ge-APD, the minimum detected pulse energy as experimentally measured, was $E = 1.5 \cdot 10^{-15}$ J ($\lambda = 1.54\,\mu$m). These results show promising nature of using SAM APDs based on the GaInAsSb/GaAl(As)Sb solid solutions for detecting the pulse laser signals within the range of the wavelength $2-3\,\mu$m [15,19,78].

The threshold sensitivity of the receiving optoelectronic module with SAM APD based on the GaAlAsSb/GaInAsSb structure for the wavelength $\lambda = 2.5\,\mu$m was calculated in [79]. In doing so, the authors have used the experimental data of our study [55]. The calculations were carried out within the temperature range 190−300 K for the two orientations of the electric field — (111) and (100). The following values of minimum detected powers were obtained at the temperature $T = 190$ K along the (111) direction: $\eta\langle P_{\text{APD}}\rangle = -50.5$ dBm for the data rate $B = 0.66$ Gb/s and $-46.4$ dBm for $B = 2$ Gb/s. According to the calculation, at $B = 0.66$ Gb/s and $T = 190$ K the noise factor was $F(M) = 2.8$ for the (111) direction and $F(M) = 4.0$ for the (100) direction. The values of the optimal multiplication coefficient were then $M_{\text{opt}} = 94$ and 52, respectively. At the room temperature and $B = 2$ Gb/s, the minimum detected power was $\eta\langle P_{\text{APD}}\rangle = -41.6$ dBm for the (111) orientation and $\eta\langle P_{\text{APD}}\rangle = -40.5$ dBm for the (100) orientation. The respective values of the excessive noise factor were $F(M) = 2.4$ at $M_{\text{opt}} = 47$ and $F(M) = 3$ at $M_{\text{opt}} = 28$. These data correlate well with the results of our study [63].

For comparison, we give results of the latest studies of Japanese researchers, who were involved in creating high-speed APDs based on the InGaAs/InAlGaAs/InAlAs structure for FOCLs and studied influence of the excessive noise on the threshold sensitivity of the optoelectronic receiving module for the range of the wavelengths $0.8-1.3\,\mu$m [80]. At the measured values of the multiplication coefficient $M = 1.5-4.5$ and the design ratio of the ionization coefficients $\alpha/\beta = 0.05-0.3$ for the data rate $B = 106$ Gb/s and the error probability $\text{BER} = 2.4 \cdot 10^{-4}$ the minimum threshold sensitivity of the receiving module was at the level of $-13.81$ dBm. These results are significantly inferior to respective characteristics for the germanium APD and for our SAM APD based on the GaInAsSb/GaAl(As)Sb heterostructure (see Fig. 11).

## 8. Conclusion

The paper presents results of many years of theoretical and experimental studies of the processes of impact ionization and heating of the charge carriers at electric field in the $A^{III}B^{V}$ semiconductors, as performed in Ioffe Institute. These pioneer studies allowed establishing a relation of the processes of impact ionization with the features of the band structure of the InAs, InSb, GaAs, GaSb, InP, AlSb semiconductors and their solid solutions and explaining the results of many experimental studies of the coefficients of impact ionization of the charge carriers, which have been carried out both by Russian and foreign scientists. It is shown that the transformation of the band structure due to the changing the composition of the solid solutions, the temperature, as well as the crystal orientation in the electric field opens up the possibility of controlling the ratio of the ionization coefficients of the charge carriers and lets choosing the optimal parameters of the materials in order to create the avalanche diodes with high amplification and a low level of excessive noise.

The high-energy asymptotics of the distribution function of the charge carriers in the semiconductors of the GaAs, InP type in the high electric field has been analytically calculated and the field dependence of the coefficient of impact ionization of electrons has been obtained. It is shown that when changing the orientation of the electric field in the crystal, the anisotropy of the energy spectrum of electrons in the conductivity band results in the anisotropy of the distribution function and the coefficients of impact ionization.

The importance of the subsidiary $X$- and $L$-valleys has been shown for the processes of impact ionization by electrons in the semiconductors and it has established a relation of the characteristic fields $E_{01}$, $E_{02}$ in the expressions for the ionization coefficients to parameters of the semiconductor material and to the constants of the intervalley interaction for scattering between the valleys $\Gamma-X$, $X-X$ and $\Gamma-L$. A method has been suggested to determine these constants from the field dependences of the ionization coefficients of electrons in the $A^{III}B^{V}$ multi-valley semiconductors. Based on the experimental data obtained for the GaAs, InP, AlGaSb semiconductor and their solid solutions, values of the constants $\Xi_{\Gamma X}$ and $\Xi_{XX}$ have been found and they agree well with the calculation results.

It has been found experimentally and confirmed by the theoretical estimations that in the semiconductors of the InAs, GaSb type and in their solid solutions, in which there is band „resonance" phenomenon i.e. the closeness of the band gap value and the value of the spin-orbit splitting of the valence band ($E_g \approx \Delta$), the processes of impact ionization and Auger-recombination are mainly contributed by holes from the spin-orbit split-off band, whose threshold of direct ionization has the lowest value ($\varepsilon_{ih} \approx \Delta$) and which can start the ionization from the zero kinetic energy.

It is established that in the materials based on GaSb and its solid solutions, whose band structure combines two features — the band „resonance" phenomenon and the presence of subsidiary low-lying $L$-valley within the conductivity band along the (111) direction, pumping out the „heavy" electrons from the $\Gamma$-valley, the maximum ratio of the ionization coefficients can be achieved due to practically monopolarity multiplication of holes with the low threshold energy from the spin-orbit split-off band ($\varepsilon_{ih} \approx \Delta \approx E_g$).

It was presented an experimental prototype of the high-speed avalanche photodiode based on the GaInAsSb/AlGaAsSb heterostructure with separated regions of absorption and multiplication in the system of the GaSb$-$InAs$-$AlSb solid solutions, which is grown on the $n$-GaSb (111) substrate, with the high ratio of the ionization coefficients of holes and electrons, which is characterized by the lowest level of excessive noise $F(M) = 1.6$ and the high response rate $1/\tau_i \sim 2 \cdot 10^{11}\,\mathrm{s}^{-1}$.

Thus, the experimental and theoretical studies devoted to investigating the relation of the ionization coefficients to the features of the band structure of the semiconductor materials, which have been carried out in Ioffe Institute, are a qualitative jump in understanding the physics of the avalanche photodiodes. It allowed formulating a fundamental physical approach to creating practically noiseless avalanche photodiode based on the $A^{III}B^{V}$ semiconductors. They are promising for application as included in the high-sensitive optoelectronic recieving modules in the high-frequency telecommunication lines, laser range finding, free space location, gas analysis and environmental monitoring, as well as for single-photon detection of weak signals of the solid-state lasers in the near- and mid-infrared regions of the spectrum.

### Conflict of interest

The authors declare that they have no conflict of interest.

## References


[1] L.V. Keldysh. ZhETF, **3** (9), 714 (1959) (in Russian).
[2] P.A. Wolf. Phys. Rev., **95**, 1415 (1954).
[3] G.A. Baraff. Phys. Rev., **163**, A36 (1964).
[4] D.J. Robbins. Phys. Status Solidi B, **97**, 387 (1980).
[5] A.P. Dmitriev, L.D. Tsendin. ZhETF, **81** (6), 2033 (1981) (in Russian).
[6] A.P. Dmitriev, M.P. Mikhailova, I.N. Yassievich. Phys. Status Solidi B, **113**, 125 (1982).
[7] G.E. Stillman, C.M. Wolfe. In: *Semiconductors and Semimetals*, ed. by R.K. Willardson and A.C. Beer (Academic Press, 1977) v. 12.
[8] F. Capasso. In: *Light-Wave Communications Technology*, ed. by W.T. Tsang. Ser. *Semiconductors and Semimetals*, ed. by R.K. Willardson and A.C. Beer (Orlando–San Diego–N.Y.–London–Toronto–Montreal–Sydney–Tokyo, Academic Press Inc., 1985) v. 22, pt. D Photodetectors, chap. 1.
[10] A.S. Tager, V.M. Wald-Perlov. *Lavinno-proletnye diody i ikh primenenie v tekhnikhe SVCh* (M., Sov. radio, 1968).
[11] A.S. Tager. Sov. Phys. Solid State, **6**, 1919 (1965).
[12] R.J. Mc Intyre. IEEE Trans. Electron. Dev., **13**, 164 (1966).
[13] M.P. Mikhailova, E.V. Ivanov, L.V. Danilov, K.V. Kalinina, Yu.P. Yakovlev, P.S. Kop'ev. Semiconductors, **54** (12), 1527 (2020).
[14] A.M. Filachev, M.A. Trishenkov, I.I. Taubkin. *Tverdotel'naya optoelectronika. Photodiody* (M., Fizmatkniga, 2011).
[15] M.P. Mikhailova, I.A. Andreev. In: *Mid-Infrared Optoelectronics*, ed. by A. Krier [*Springer Ser. in Optical Sciences* (London, Springer Verlag, 2006) p. 47].
[16] A.P. Dmitriev, M.P. Mikhailova, I.N. Yassievich. V sb.: *Photopriemniki i photopreobrazovateli* (L., Nauka, 1986) s. 67 (in Russian).
[17] V.I. Korol'kov, M.P. Mikhailova. FTP, **17**, 569 (1983) (in Russian).
[18] V.I. Korol'kov, M.P. Mikhailova, S.V. Ponomarev. Elektron. tekhn., ser. 4, №. 1 (100), 31 (1984) (in Russian).
[19] M.P. Mikhailova, K.D. Moiseev, Yu.P. Yakovlev. Semiconductors, **53** (3), 273 (2019).
[20] J.L. Moll, R. van Overstraeten. Solid-State Electron., **6**, 44 (1962).
[21] A.S. Tager. FTP, **6** (8), 2418 (1964) (in Russian).
[22] M.L. Cohen, T.K. Bergstresser. Phys. Rev., **141** (2), 489 29 (1966).
[23] J.R. Chelikovsky, M.L. Cohen. Phys. Rev. B, **14**, 556 (1976).
[24] Z.S. Gribnikov. ZhETF,**24**, 2112 (1978) (in Russian).
[25] *Mnogodolinnye poluprovodniki*, pod red. Yu.K. Pozhela (Vilnyus, Mokslas, 1978) t. 1 (in Russian).
[26] Y. Pozela, A. Rektaitis. Solid-State Electron., **23**, 927 (1980).
[27] A.V. Garmatin, A.A. Kalfa, A.S. Tager. FTP, **13**, 2251 (1979).
[28] M.P. Mikhailova. *Tez. dokl. V Simp. Plazma i neustoichivosti v poluprovodnikakh* (Vilnyus, 1983) s. 144 (in Russian).
[29] A.P. Dmitriev, M.P. Mikhailova, I.N. Yassievich. Pis'ma ZhTF, **7** (24), 1505 (1981) (in Russian).
[30] A.P. Dmitriev, M.P. Mikhailova, I.N. Yassievich. FTP, **17** (5), 875 (1983) (in Russian).

[31] A.P. Dmitriev, M.P. Mikhailova, I.N. Yassievich. FTP, **17** (1), 46 (1983) (in Russian).
[32] M.E. Levinshtein. FTP, **13**, 1249 (1979) (in Russian).
[33] T.P. Pearsall, R.E. Nahory, M.A. Pollack. Appl. Phys. Lett., **28** (7), 403 (1976).
[34] T.P. Pearsall, R.E. Nahory, J.R. Chelikowsky. Phys. Rev. Lett., **39**, 295 (1977).
[35] H. Shichijo, K. Hess. Phys. Rev. B, **23** (8), 4197 (1981).
[36] K. Hess, J.Y. Tang, K. Brennan, H.Shichijo, G.E. Stillman. J. Appl. Phys., **53** (4), 3327 (1982).
[37] F. Capasso, T.P. Pearsall, K.K. Thornber, R.E. Nahory, M.A. Pollack, G.B. Bachelet, J.R. Chelikowsky. J. Appl. Phys., **53** (4), 3324 (1982).
[38] *Handbook Series of Semiconductor Parameters*, ed. by M. Levinstein, S. Rumyantsev, M. Shur (Singapore–N.Y.–London–Hong Kong, World Scientific Publishing, 1996) v. 1.
[39] I. Vurgaftman, J.R. Meyer, L.R. Ram-Mohan. J. Appl. Phys., **89** (11), 5815 (2001).
[40] E. Antončik. Czech. J. Phys., **B17**, 775 (1967).
[41] E.O. Kane. J. Phys. Chem. Solids, **1**, 249 (1957).
[42] A.R. Beattie. J. Phys. Chem. Solids, **23**, 1049 (1962).
[43] R.D. Baertch. J. Appl. Phys., **38**, 4267 (1967).
[44] W.P. Dumke. Phys. Rev., **167**, 783 (1968).
[45] V.V. Gavrushko, O.V. Kosogov, V.D. Lebedev. FTP, **12**, 2351 (1978) (in Russian).
[46] A.A. Gutkin, O.V. Kosogov, S.E. Kumekov. Sov. Phys. Semicond., **14** (6), 1161 (1980).
[47] G. Lukovsky, R.B. Emmons. Proc. IEEE, **53**, 180 (1965).
[48] M.P. Mikhailova, D.N. Nasledov, S.V. Slobodchikov. FTP, **1**, 123 (1967) (in Russian).
[49] M.P. Mikhailova, S.V. Slobodchikov, N.N. Smirnova, G.M. Filaretova. FTP, **10**, 978 (1976) (in Russian).
[50] M.P. Mikhailova, A.A. Rogachev, I.N. Yassievich. FTP, **10**, 1480 (1976) (in Russian).
[51] N.V. Zotova, I.N. Yassievich. FTP, **11**, 1882 (1977) (in Russian).
[52] I.A. Andreev, M.P. Mikhailova, A.N. Semenov, S.V. Slobodchikov, N.M. Stus', G.M. Filaretova. FTP, **18** (3), 545 (1984) (in Russian).
[53] O. Hilderbrandt, W. Kuebart, K.W. Benz, M.H. Pilkuhn. IEEE J. Quant. Electron., **QE-17** (2), 284 (1981).
[54] M.Z. Zhingarev, V.I. Korol'kov, M.P. Mikhailova, I.N. Yassievich. Pis'ma ZhTF, **5**, 862 (1979) (in Russian).
[55] M.Z. Zhingarev, V.I. Korol'kov, M.P. Mikhailova, V.V. Sazonov. Pis'ma ZhTF, **7** (24), 1487 (1981) (in Russian).
[56] C.H. Grein, H. Ehrenreich. Appl. Phys. Lett., **77** (19), 3048 (2000).
[57] G. Lecoy, B. Orsal, R. Alabedra. IEEE J. Quant. Electron., **23** (7), 1145 (1987).
[58] M.P. Mikhailova, D.N. Nasledov, S.V. Slobodchikov. FTP, **10**, 860 (1976) (in Russian).
[59] B.A. Matveev, M.P. Mikhailova, S.V. Slobodchikov, N.N. Smirnova, N.M. Stus', G.N. Talalakin. FTP, **13** (3), 499 (1979) (in Russian).
[60] V.M. Andreev, M.Z. Zhingarev, O.O. Iventieva, V.I. Korol'kov, M.P. Mikhailova. FTP, **15** (6), 1215 (1981) (in Russian).
[61] N. Susa, H. Nakagome, H. Mikamo, O. Ando, N. Kanbe. IEEE J. Quant. Electron., **16**, 864 (1980).
[62] Y. Takanashi, M. Kawashima, Y. Horikoshi. Jpn. J. Appl. Phys., **19**, 693 (1980).
[63] M.P. Mikhailova, I.A. Andreev, E.V. Kunitsyna, Yu.P. Yakovlev. Proc. SPIE, **7355**, 735511 (2009).
[64] I.A. Andreev, M.P. Mikhailova, S.V. Mel'nikov, Yu.P. Smorchkova, Yu.P. Yakovlev. FTP, **25** (8), 1429 (1991) (in Russian).
[65] T.I. Voronina, T.S. Lagunova, E.V. Kunitsyna, Ya.A. Parkhomenko, D.A. Vasyukov, Yu.P. Yakovlev. FTP, **35** (8), 941 (2001) (in Russian).
[66] E.V. Kunitsyna, I.A. Andreev, G.G. Konovalov, E.V. Ivanov, A.A. Pivovarova, N.D. Il'inskaya, Yu.P. Yakovlev. Semiconductors, **52** (9), 1215 (2018).
[67] I.A. Andreev, M.A. Afrailov, A.N. Baranov, N.N. Mar'inskaya, M.A. Mirsagatov, M.P. Mikhailova, Yu.P. Yakovlev. Pis'ma ZhTF, **15** (17), 71 (1989) (in Russian).
[68] V. Diadiuk, S.H. Groves, C.E. Hurwitz. Appl. Phys. Lett., **37** (9), 807 (1980).
[69] H. Law, K. Nakano, L. Tomasetta. IEEE J. Quant. Electron., **QE-15** (7), 549 (1979).
[70] T. Kaneda. In: *Lightwave Communications Technology*, ed. by W.T. Tsang. Ser. *Semiconductors and Semimetals*, ed. by R.K. Willardson and A.C. Beer (Orlando–San Diego–N. Y.–London–Toronto–Montreal–Sydney–Tokyo, Academic Press Inc., 1985) v. 22, pt D Photodetectors, chap. 3.
[71] I.A. Andreev, M.A. Afrailov, A.N. Baranov, S.G. Konnikov, M.A. Mirsagatov, M.P. Mikhailova, O.V. Salata, V.B. Umanskiy, G.M. Filaretova, Yu.P. Yakovlev. Pis'ma ZhTF, **15** (7), 15 (1989) (in Russian).
[72] F. Ma, S. Wang, X. Li, K.A. Anselm, X.G. Zheng, A.L. Holmes, J.C. Campbell. J. Appl. Phys., **92** (8), 4791 (2002).
[73] M.E. Woodson, M. Ren, S.J. Maddox, Y. Chen, S.R. Bank, J.C. Campbell. Appl. Phys. Lett., **108** (8), 081102 (2016).
[74] M. Ren, S.J. Maddox, M.E. Woodson, Y. Chen, S.R. Bank, J.C. Campbell. Appl. Phys. Lett., **108** (19), 191108 (2016).
[75] S.R. Forrest. In: *Light-Wave Communications Technology*, ed. by W.T. Tsang. Ser. *Semiconductors and Semimetals*, ed. by R.K. Willardson and A.C. Beer (Orlando–San Diego–N. Y.–London–Toronto– Montreal–Sydney–Tokyo, Academic Press Inc., 1985) v. 22, pt D *Photodetectors*, chap. 4.
[76] R.C. Smith, S.D. Personick. In: *Semiconductor Devices for Optical Communications*, ed. by H. Kressel. Ser. *Topics in Appl. Phys.* (Berlin, Springer Verlag, 1982) v. 39, p. 89.
[77] I.A. Andreev, A.N. Baranov, M.V. Voznitskiy, M.P. Mikhailova, T.N. Sirenko, Yu.P. Yakovlev. Opt.-mekh. prom., **7**, 19 (1991) (in Russian).
[78] A.M. Filachev, M.A. Trishenkov, I.I. Taubkin. *Sostoyanie i magistral'nye napravleniya razvitiya tverdotel'noy elektroniki* (M., Fizmatkniga, 2010).
[79] J. Benoit, M. Boulou, C. Soulage, J. Jullie, H. Mani. J. Opt. Commun., **9** (2), 5558 (1988).
[80] M. Nada, F. Nakajima, T. Yoshimatsu, Y. Nakanishi, S. Tatsumi, Y. Yamada, K. Sano, H. Matsuzaki. Appl. Phys. Lett., **116**, 140502 (2020).