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The role of diffusion of photoexcited electrons from heavily doped layers in the photoconductivity of AlAs/GaAs heterostructures

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Based on the study of photoconductivity in GaAs / AlAs $p-i-n$ heterostructures in the visible light range, the dominant role of the diffusion channel of photoexcited electrons from heavily doped layers in the formation of photocurrent oscillations from the bias voltage and the determining contribution of this channel to the total current through the structure is shown. A qualitative model of the transport of excited carriers is considered, which assumes the diffusion channel as the main source of photooscillations.

Keywords: heterostructures, photoconductivity.

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1. Introduction

Semiconductor $p-i-n$ heterostructures are widely used as radiation detectors and have multiple applications in optoelectronics [1–4]. Absorption of light with energy higher than the forbidden band width in such semiconductor structures results in generation of electron-hole pairs. Pairs, generated in depleted i-area or at a distance of about diffusion length from i-area into the depth of doped n- and p-layers, are divided with electrical field, and as a result the current appears in external circuit [4]. Photocurrent value will be defined with drift current of carriers, generated in i-area, and diffusion currents of carriers, generated outside i-area. Under certain conditions the photoresponse of semiconductor structures can detect multiple various quantum oscillating events. For instance, relaxation of energy of photoexcited electrons and holes due to optical phonon emission results in photocurrent oscillations depending on energy of exciting photons [5]. Photocurrent oscillations from bias voltage were observed in GaAs/AlAs or InGaN/GaN $p-i-n$ superlattices [6,7]. In the work [8] the influence of InAs layer of quantum dots in i-area of $p-i-n$-diode on photoresponse spectra was studied and efficiency of such heterosystem for creation of sensitive photodetectors is shown. Later, in such single-barrier GaAs/AlAs heterostructures (see Fig. 1) the gigantic photocurrent oscillations [9,10] were observed at irradiation with light with photon energy higher than forbidden band width in GaAs, which appeared as multiple resonance-like peculiarities on volt-ampere characteristics (VAC). Amplitude of such oscillations was 20% of average value of photocurrent at irradiation with light with wavelength of $\lambda = 650\,\mathrm{nm}$, while in $p-i-n$-diodes with single tunneling barrier it is a priori impossible to assume presence of any photocurrent resonances. It was observed, that period of such oscillations is defined exclusively by a length of i-area, enclosed between AlAs barrier and p^+-contact. These photocurrent oscillations were qualitatively interpreted in [9] as a consequence of modulation of a rate of carriers recombination in moments of correspondence of levels of triangular quantum well, formed in non-doped near-barrier i-area, and bottom of conductivity band of heavily doped p^+-layer with electrical field change. Schematic energy band diagram of heterostructure active area at bias voltage $V_b < 1.5\,\mathrm{V}$ ($V_b \approx 1.5\,\mathrm{V}$ corresponds to flat bands condition) is shown in Fig. 1. Change of V_b towards negative values, starting from $V_b \approx 1.5\,\mathrm{V}$, results in movement of electron size quantization levels E_j in triangular quantum well (TQW) upwards along the energy relating to its bottom, but downwards relating to conductivity band edge E_C, restricting this well from the right, resulting in sequential addition on new levels of E_j with energy $\approx E_\mathrm{C}$ to TWQ (see Fig. 1, a). With increase of electrical field in i-area the certain electron state E_j in triangular quantum well approaches the top of its triangular potential well, and its wave function progressively penetrates the region with high density of the main holes in the doped electrode of p^+-GaAs. In model from [9] it was assumed, that overlap increases rate of photoexcited electrons recombination on E_j-level of TWQ, thus reducing their contribution to photocurrent at tunneling through AlAs barrier. Therefore, with change of V_b the electrons recombination rate periodically changes, inducing photocurrent oscillations, i.e. in moments of E_j correspondence with E_C the photocurrent sharply reduces. It should be noted, that generation of electron-hole pairs is considered in this model only in the area of electrical field existing, i.e. in i-area, while the possible diffusion current of electrons from p^+-area and holes from n^+-area was neglected, since it was considered that time of carriers

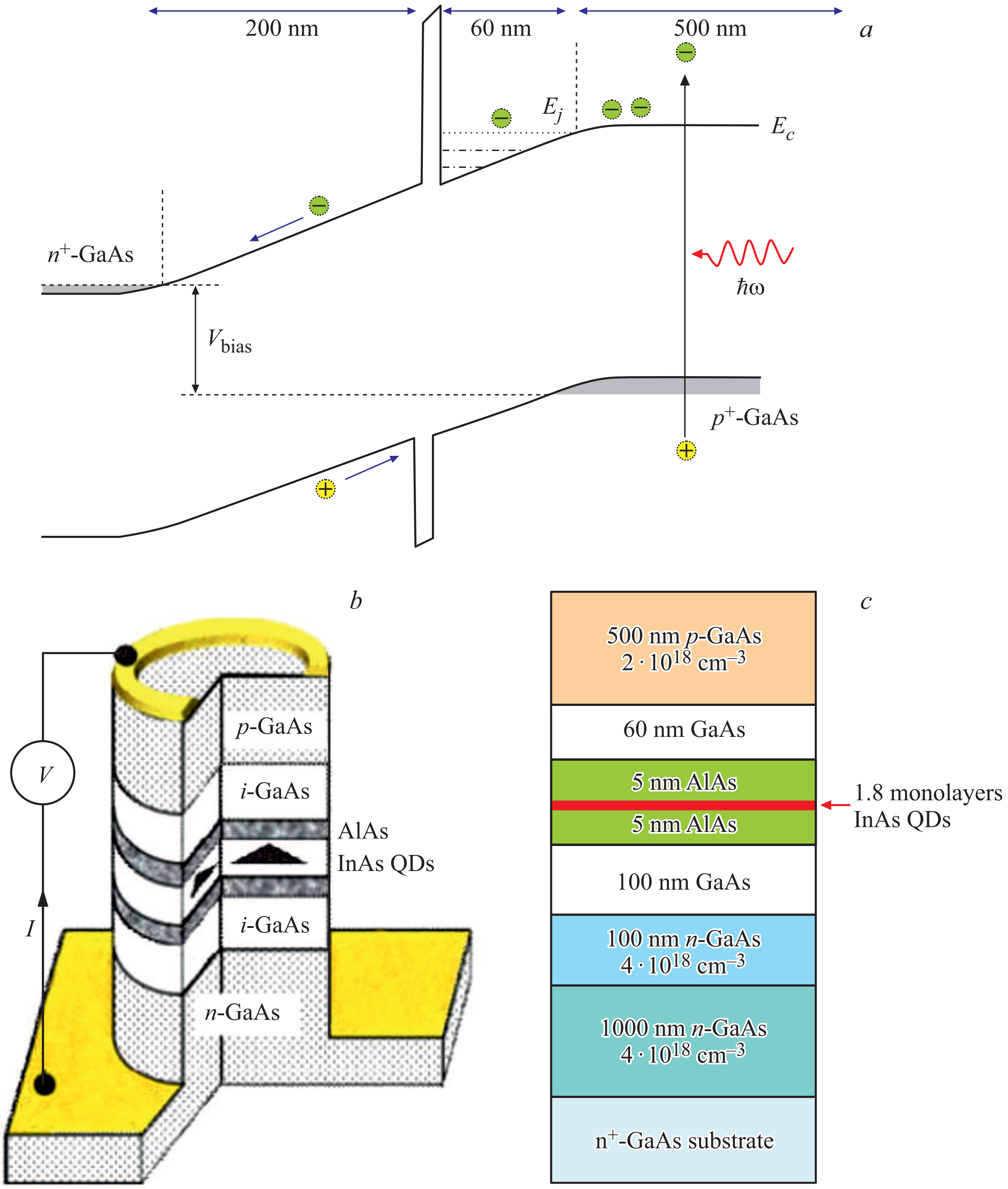

Figure 1. *a*) Energy band diagram of experimental sample at $V_b < 1.5$ V. Arrows show processes of photogeneration of electron-hole pairs and carriers movement in electrical field. Dashed lines — size quantization levels E_j in triangular quantum well, and E_C — bottom of conductivity band in contact p^+-layer; *b*) schematic section of experimental mesastructure and photocurrent measurement scheme; *c*) schematic representation of sequence, materials and thicknesses of heterostructure layers with notification of doping concentration in contact layers.

diffusion to *i*-area is much higher than lifetime of non-main carrier in heavily doped p^+-area (or n^+-area). This assumption contradicts with the common description of photodetection in $p-i-n$–diodes [4], but, since it was observed, that photooscillations period depended on triangular quantum well width only, such model described the observed effect sufficiently realistic. However, our further studies [11] showed, that dependence of ratio of contributions of oscillating and non-oscillating components of photocurrent $I_{\text{osc}}/I_{\text{fon}}$ on power can not be described within a model [9], where ratio $I_{\text{osc}}/I_{\text{fon}}$ does not depend on radiation intensity and for consistent description of all presented experiments the new qualitative model of oscillations formation, including the diffusion transport of photoexcited electrons from *p*-layer as the main element, was proposed.

Behavior of photocurrent oscillations in GaAs/AlAs $p-i-n$ heterostructures in a visible light range of wavelengths is studied in this work. It is shown, that photocurrent oscillations from bias voltage are formed due to diffusion of electrons, excited by a light in p^+-area and arrived to the edge of the triangular quantum well with energy, corresponding with the top level in the well; while value of non-oscillating photocurrent component is defined by additive contributions of charge carriers, excited with a light in the rest heterostructure regions. Qualitative model of excited carriers transport, assuming diffusion channel as the main source of photooscillations, is examined.

2. Samples and experimental procedure

Samples, examined by us, were made based on single-barrier GaAs/AlAs $p-i-n$ heterostructures with non-doped i-layers of 60 and 100 nm from the side of p^+- and n-areas, respectively, grown using molecular-beam epitaxy method. Barrier level of AlAs with thickness of 5 nm is located between non-doped i-layers.

Upper p^+-layer of GaAs with thickness of $0.5\,\mu$m is doped to concentration of $2 \cdot 10^{18}\,\text{cm}^{-3}$. Such structures are described in detail in the works [9,10]. Standard chemical etching technology was used for creation of optical mesastructures with diameter of $25-200\,\mu$m. Figure 1, *b* schematically shows the section of experimental mesastructure and photocurrent measurement scheme, while in Fig.1, *c* — the schematic representation of sequence, materials and thicknesses of heterostructure layers with notification of doping concentrations in contact layers. Ohmic contacts were made by means of successive evaporation of AuGe/Ni/Au layers and annealing at $T = 400°$C. Volt-ampere characteristics (VAC) were measured at noise level of less than 100 fA. Measurements were made at temperature of 4.2–100 K. Samples were irradiated with light with wavelengths in a range λ from 650 and 405 nm from the heavily doped p^+-area. Spectrophotometer was used in wavelength interval λ from 875 to 650 nm and set of LEDs was used in the interval from 650 to 405 nm as light radiation sources.

3. Study results and their discussion

Figure 2 shows the reverse branches of VAC of our experimental sample in the region of $V_b < 1.5$ V at 8 values of acting radiation power P from 3 to 85 nW with wavelength $\lambda = 650$ nm and at $T = 4.2$ K. Without lighting the reverse branches of VAC presented monotonic dependencies without any visible peculiarities, dark current in interval below 3 V did not exceed 10 pA and, probably, was defined mainly with the processes, similar for $p-n$-transition generation current. Light radiation exposure to the samples with λ until 840 nm did not make any significant impact on VAC. When λ became less than 824 nm (that approximately corresponds to GaAs forbidden band width), reverse branches of VAC started to demonstrate the oscillating component with amplitude, proportional to P, and period, not dependent on λ, similar to [9]. Both oscillation amplitude and non-oscillating „background“ photocurrent linearly depended on radiation power, as seen in Fig. 2, *b*, where dependence of amplitude $(I_{\max} - I_{\min})$ and background current $(I_{\max} + I_{\min})/2$ on power for oscillation near $V_b \sim 0$ V at $\lambda = 650$ nm and $T = 4.2$ K is shown. With reduction of a light wavelength the photocurrent grew similar [8] to $\lambda \sim 750$ nm with the further sharp drop to 405 nm, but dependence of oscillations amplitude and background current on power continued to be linear. Figure 3, *a* shows VAC of the sample at lighting with $\lambda = 650$ nm (red dots) and 405 nm (purple line). We can see, that for the non-oscillating component of photocurrent of these two wavelengths to be almost the same, the purple light power should be increased almost in 55 times relating to red light power. It should be noted, that photocurrent oscillations amplitude under these conditions for $\lambda = 405$ nm is almost twice higher, that for $\lambda = 650$ nm. We will discuss this increase of photooscilaltions amplitude later, and now it

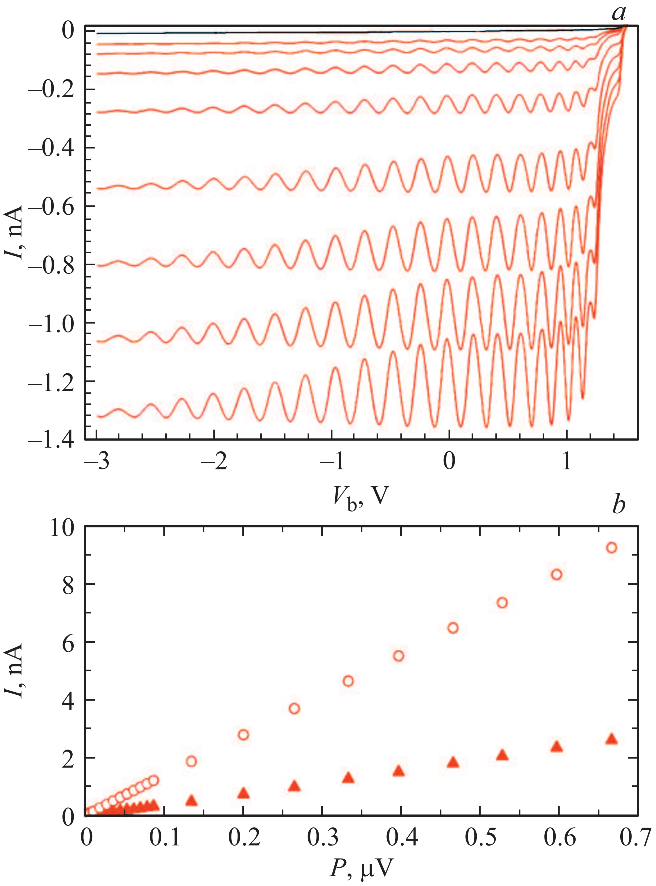

Figure 2. *a*) VAC of experimental sample in the region of $V_b < 1.5$ V at 8 values of acting radiation power $P = 3$, 5, 10, 20, 35, 50, 70, 85 nW with wavelength $\lambda = 650$ nm and at $T = 4.2$ K; *b*) dependence of amplitude $(I_{\max} - I_{\min})$ and background current $(I_{\max} + I_{\min})/2$ on power for oscillation near $V_b \sim 0$ V at $\lambda = 650$ nm and $T = 4.2$ K.

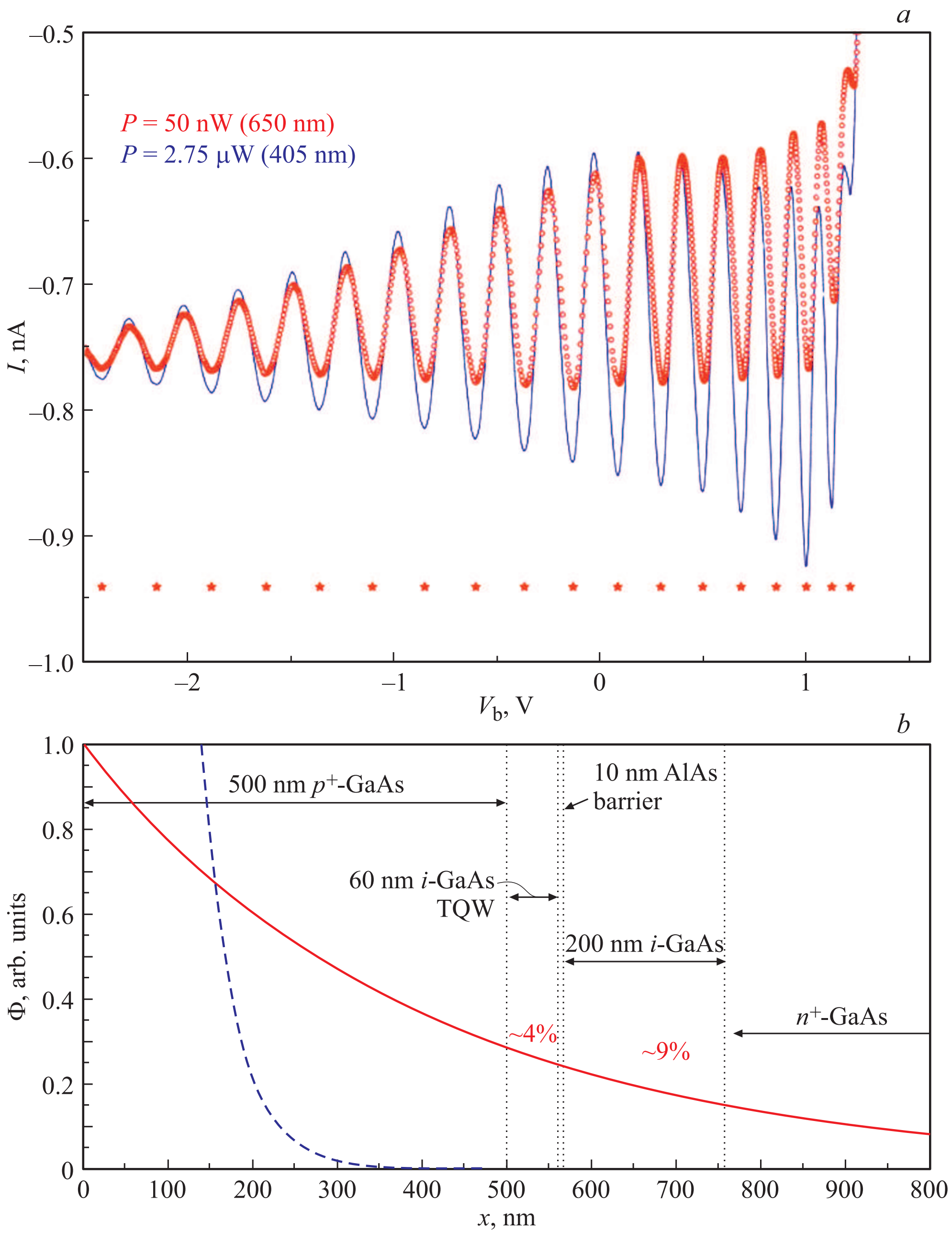

Figure 3. *a*) VAC of the sample at lighting with $\lambda = 650$ nm (red dots) at $P = 50$ nW and 405 nm (purple line) at $P = 2.75\,\mu$W at $T = 4.2$ K. The asterisks indicate positions for V_b of absolute values of photocurrent maximums; *b*) photons absorption curves, calculated as per formula $\Phi \propto \Phi_0 \exp(-ax)$ for $\lambda = 650$ nm (red curve) and 405 nm (purple curve) at $P_{405} = 55P_{650}$ along layers (along x axis) of experimental structure.

should be noted, that in this case within the model, proposed in the work [9], where carriers pairs generation is considered in i-area only, the existing of the oscillating component of photocurrent is absolutely impossible, since the light absorption coefficient has spectral dependence and for purple light is about $\alpha \sim 10^5\,\mathrm{cm}^{-1}$ [12], and majority of photons are absorbed near sample surface, not reaching the triangular quantum well.

Figure 3, *b* shows the photons absorption curves $\Phi \propto \Phi_0 \exp(-ax)$ for $\lambda = 650$ nm (red curve) and 405 nm (purple curve) at $P_{405} = 55P_{650}$ and layers of our experimental structure, laid along x axis. To explain the scale of influence of λ on absorption depth in our structure it should be noted that for $\lambda = 405$ nm less than 1% of photons could go deep to p^+-layer to distance of $0.2\,\mu$m, while for $\lambda = 650$ nm the same share of photons goes deep to n^+-layer (up to $\sim 2\,\mu$m), and about 15% go through both i-layers and reach boundary with n^+. Thus, the observance of photocurrent oscillations at $\lambda = 405$ nm clearly indicates the inapplicability of their origin model from [9] and necessity of its reconsideration. It should be however noted, that even for red light the photons absorption consideration only in i-area of our structure gives low quantum detection efficiency $< 15\%$, while for the similar structure in the work [8] the quantum efficiency of about 30–40% was defined, that indicates the necessity of consideration of carriers drift from p^+- and n^+-areas and for $\lambda = 650$ nm.

We propose a new qualitative model based on a mechanism of resonance amplification of passage of electrons, diffused from the depth of p-layer through levels in quantum well, similar to resonance tunneling through wide QWs [13]. Since lifetime of photoexcited electrons near surface is low, most of them recombine before reaching i-area using diffusion and contributing to photocurrent. But with high radiation power the sufficient amount of electrons, that are generated in p^+-layer with thickness of $0.5\,\mu$m, will be able to diffuse to i-area and, after coinciding with E_j level in triangular QW, to tunnel through barrier resonantly, creating photocurrent oscillations. I.e. each time, when a new E_j level enters QW with electrical field growth and coincides with E_{C}, the sharp resonance increase of rate of tunneling through barrier happens for electrons, excited in a depth of heavily doped contact p^+-layer and reached, as a result of diffusion and drift, the edge of triangular well, resulting in photocurrent surge. At the same time, the oscillations amplitude is defined with a number of electrons, excited with a light in p^+-area and arrived to the edge of the triangular quantum well with energy E_{C}, while value of non-oscillating photocurrent component is defined by additive contributions of charge carriers, excited with a light with a certain wavelength in the rest regions of heterostructures active part.

Value of photooscillations for $\lambda = 405$ nm, larger than for $\lambda = 650$ nm, at the fixed value of non-oscillating current (see Fig. 3, *a*) also confirms, that photocurrent oscillations from bias voltage in our $p{-}i{-}n$ structures are caused by diffusion of electrons, excited with a light in p^+-area and arrived to the edge of the triangular quantum well with energy E_{C}. Since „background current“ is a sum of non-resonance current through TQW and current of carriers, originated in i- and n-areas, with a light wavelength increase it grows due to larger light penetration through structure and increase of number of pairs, generated in i-layers, resulting in relative reduction of photocurrent oscillations amplitude. Figure 4, *a* shows the values of $(I_{\max} - I_{\min})$ for oscillation near $V_b \sim 0$ at structure lighting with λ from 650 to 405 nm, for the „background current“ to be equal to 1 nA. Monotonic relative increase of oscillation amplitude with decrease of λ is explained with the abovementioned reduction of I_{fon} due to less light penetration through structure and reduction of number of pairs, generated in i-layers.

Good agreement of voltage ladder V_b, corresponding to oscillations extremes, with a sequence of coincidence moments for E_j and E_{C} is shown in our first work [9], and similar calculation, made by us for this heterostructure, is presented in Fig. 4, *b*.

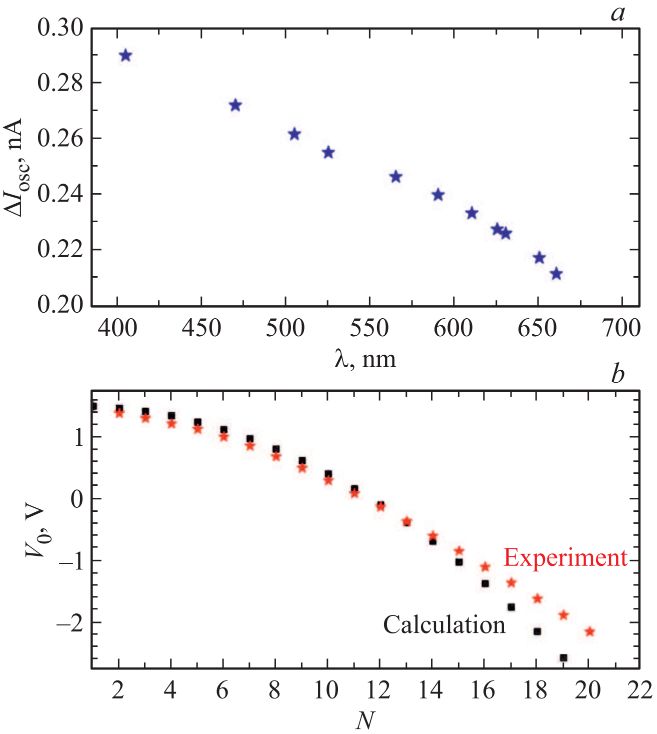

Figure 4. *a*) Oscillation amplitude $(I_{\max} - I_{\min})$ at $V_b \sim 0$ at structure lighting with LEDs with λ from 650 to 405 nm under equality condition $I_{\text{fon}} = 1$ nA; *b*) comparison of calculated and experimental values of oscillations position as per V_b.

But while in the old model we observe the sharp drop of photocurrent in this moment, in assumption of resonance tunneling of photoexcited electrons, coming from the depth of p^+-area, the maximum of photocurrent will correspond to this moment. Electrostatic model, that we used for calculation of coincidence moments for E_j and E_{C} [9,10], does not give us an opportunity to make a choice between these two oscillation mechanisms, since we can not calculate a position of oscillations minimums and maximums with accuracy of half-period due to impossibility of correct consideration of charge accumulation in AlAs barrier at defects and quantum wells in a barrier and complications of measurement of the first oscillation in the moment of TQW formation. But even these calculations confirm, that photocurrent oscillations extremes position is defined by TQW design only.

4. Conclusion

As a result, we studied behavior of quantum oscillations of photocurrent in GaAs/AlAs $p{-}i{-}n$ heterostructures at exposure of a light with wavelengths λ in interval from 875 to 405 nm. The dominant role of diffusion channel of photoexcited electrons from heavily doped p^+-layer during photocurrent oscillations formation from bias voltage and the defining contribution of this channel to total current through structure are demonstrated.

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Conflict of interest

The authors declare that they have no conflict of interest.

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