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Features of microwave photoconductance of quantum point contact

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Microwave photoconductance of a quantum point contact has been experimentally studied in both tunnel and open modes. It demonstrates a range of features such as change of sign during the transition from the tunnel to the open mode, display of a step structure, and varying width of the giant photoconductance region. Occurrence of the features is determined by specific implementation of the electrostatic potential, which depends both on the technologically specified structure of the grown quantum wells with two-dimensional electron gas and on the sample cooling procedure.

Keywords: nanostructures, two-dimensional electron gas, quantum point contact, photoconductance.

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1. Introduction

Quantum point contacts (QPCs), which came into use in the physics of low-dimensional electronic systems more than 30 years ago [1,2], long ago became the subject of not only numerous reviews [3–6], but also textbooks [7]. Recently, the experimental and theoretical study of the response of quantum point contact to the influence of microwave and terahertz radiation received particular relevance, since the QPC turned out to be an excellent model system for studying the quantum transmission of electron waves through a single barrier in the field of electromagnetic radiation and, in particular, of photon-stimulated tunneling (PST) [8–11]. Within the framework of the PST theory, many resonance effects were predicted using the energy dependences of coefficients of electron transmission through various nanostructures in high-frequency (HF) fields of light, IR, terahertz and microwave ranges [12–21]. Note that the most physically simple case of a single smooth barrier was not considered in the listed papers. In the paper [22] that is important for understanding the physics of photon-stimulated transport (PST) through a tunnel barrier, only a rectangular barrier was considered. We are talking about a potential that was proposed by Eckart back in the years when quantum mechanics was suggested [23] and has a simple analytical form $U(x) = U_0/\,\mathrm{ch}^2(x/W)$. As it is well known [24], in such potential there are no quasi-levels, over-barrier resonances and resonant peaks in the transmission coefficient $D(E)$. The first numerical calculations showed that photon-stimulated tunneling through the Eckart barrier, due to its smooth shape and finite height, occurs in another way than in the case of a high rectangular barrier. The PST study in such a simple potential became especially interesting after the creation of the quantum point contact based on a two-dimensional electron gas and the conductance quantization discovery in it. The results of numerical simulations of QPC electrostatics show that the shape of the barrier through which electrons fly is close to the Eckart potential. Experimentally, the photoresponse of QPCs was previously studied, but measurements were limited mainly to open $G \geq e^2/h$ and subthreshold $G < e^2/h$ transmission modes and orientation of the terahertz field across the current to observe the effects of intersubband excitation. A small effect of terahertz fields on the quantization of the QPC conductance was found, which was explained either by rectification effects or by heating of the two-dimensional electron gas upon radiation absorption. The situation changed radically when the giant microwave [8] and terahertz [9] QPC photoconductance in the tunnel mode was discovered, and the experimental and theoretical study of the QPC response to microwave and terahertz radiation received a new impetus [25–27,10]. The main objective of this paper is to experimentally study the features of QPCs microwave photoconductance in situation where they are fabricated based on AlGaAs/GaAs heterostructures and AlGaAs/GaAs/AlGaAs quantum wells having different structures of their constituent impurity and semiconductor layers in order to answer the question: whether microwave and the terahertz response of actual QPC is universal and is described by the model Eckart potential or there are features in its behavior that depend both on the technology of its manufacture and on the specific experimental situation.

2. Results and discussion

To solve this problem, the paper studied the microwave photoconductance (PC) of quantum point contacts made on the basis of three different types of structures with two-dimensional electron gas: 1) single AlGaAs/GaAs heterojunction with two δ-doping layers in AlGaAs, 2) single AlGaAs/GaAs heterojunction with a complex superlattice structure of doping layers in AlGaAs barrier and 3) double AlGaAs/GaAs/AlGaAs heterojunction with GaAs quantum well, with the same structure of doping layers in AlGaAs barriers as in the second case (Figure 1). The electron concentration N_s, their mobility μ and the corresponding mean free path l were for the two-dimensional electron gas of the first group of structures:

$$N_s = (3-4) \cdot 10^{11}\,\text{cm}^{-2},$$

$$\mu = (2-3) \cdot 10^5\,\text{cm}^2/\text{Vc}, \quad l = (2-3)\,\mu\text{m};$$

for two-dimensional electron gas of the second group:

$$N_s = (2-3) \cdot 10^{11}\,\text{cm}^{-2},$$

$$\mu = (1-2) \cdot 10^6\,\text{cm}^2/\text{Vc}, \quad l = (5-10)\,\mu\text{m}$$

and for two-dimensional electron gas of the third group:

$$N_s = (7-8) \cdot 10^{11}\,\text{cm}^{-2},$$

$$\mu = (1-2) \cdot 10^6\,\text{cm}^2/\text{Vc}, \quad l = (20-30)\,\mu\text{m}.$$

QPCs were manufactured using technology of split-gate, placed between the potentiometric contacts of the Hall bridge, using explosive electron lithography on Au/Al (see insert to Figure 2, a). Microwave radiation with a frequency of 2.44 GHz was supplied to the Hall structure from the side via a coaxial cable, which was located in few millimeters from the structure under study, and the cable screen was grounded along with one of the current contacts to the two-dimensional electron gas. In the experiment, to check the absence of parasitic effects, a circuit was also used where the current and potentiometric contacts were shunted at high frequency by capacitors. This circuit gave the same photoresponse. Conductance (G) was measured using a conventional lock-in setup at frequencies 2–6 Hz and at measuring current values of 0.001–10 nA depending on the measurement conditions. In this paper groups of three to four samples corresponding to each type of initial heterostructure were studied, and they demonstrated the same behavior within each group.

Typical QPC conductance vs. effective gate voltage V_g^{eff} ($V_g^{eff} = V_g - V_g(G_0)$, where $V_g(G_0)$ — gate voltage at which conductance is G_0) in open mode is shown in Figure 2, a. It clearly demonstrates the quasi-plateau corresponding to quantization $G = i \cdot G_0$ ($G_0 = 2e^2/h$) with i = 1, 2, 3, 4 and 5. The results of dark conductance measurements (G_{dark}) in the tunnel mode and during the transition from it to open mode for all types of initial heterostructures are presented in Figure 2, b. As it is clearly seen, in all situations, a qualitatively identical behavior of this conductance is observed: in the tunnel mode the conductance depends on V_g mainly in an exponential way; then, during transition to the open mode, the dependence

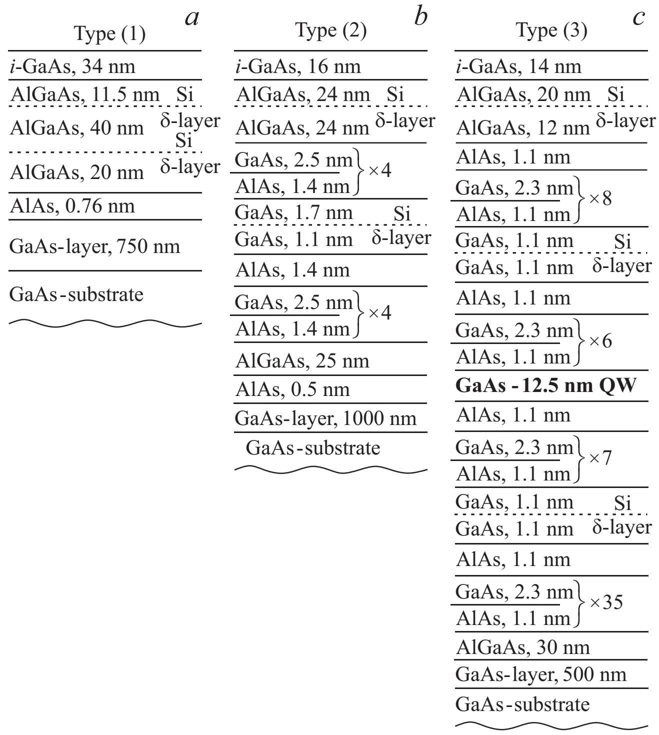

Figure 1. a) — single AlGaAs/GaAs heterojunction with two δ-layers of silicon in AlGaAs, b) — single AlGaAs/GaAs heterojunction with complex superlattice structure of doping layers in AlGaAs and c) — double AlGaAs/GaAs/AlGaAs heterojunction with GaAs quantum well and complex superlattice structure of doping layers in AlGaAs.

becomes significantly weaker, becoming almost linear in the open mode. However, a more careful analysis of all dark dependencies $G_{dark}(V_g^{eff})$ shown in Figure 2, b indicates that the behavior of such dependence for QPCs made on the basis of double heterojunction has the feature that breaks the monotonic character when in the tunnel mode on the dependence $G_{dark}(V_g^{eff})$ the break points appear. Most likely, they indicate that when the gate voltage changes in such QPCs, recharging of the doping layers in the barrier layers also occurs, associated with the low activation energy of the impurities that form them.

Let us describe now the results of measurement of photoconductance G_{ph} (Figure 3). It is clearly seen that the qualitative picture of the photoresponse is the same for all types of QPC: a gigantic increase in dark conductance under the influence of radiation in the tunnel mode is observed ($10 < G_{ph}/G_{dark} < 10^3$ at $10^{-3} < G_{dark}/G_0 < 10^{-1}$ and $G_{ph}/G_{dark} > 10^3$ at $G_{dark}/G_0 < 10^{-4}$), caused by the fact that the radiation leads to a parallel shift to the left of the measured dependence $G(V_g)$; and a significantly weaker response, as would be expected, is observed in the open state. A more careful analysis shows that the behavior of the photoresponse depends on the type of the initial quantum well with two-dimensional electron gas. Let us start with consideration of the photoconductance of QPCs

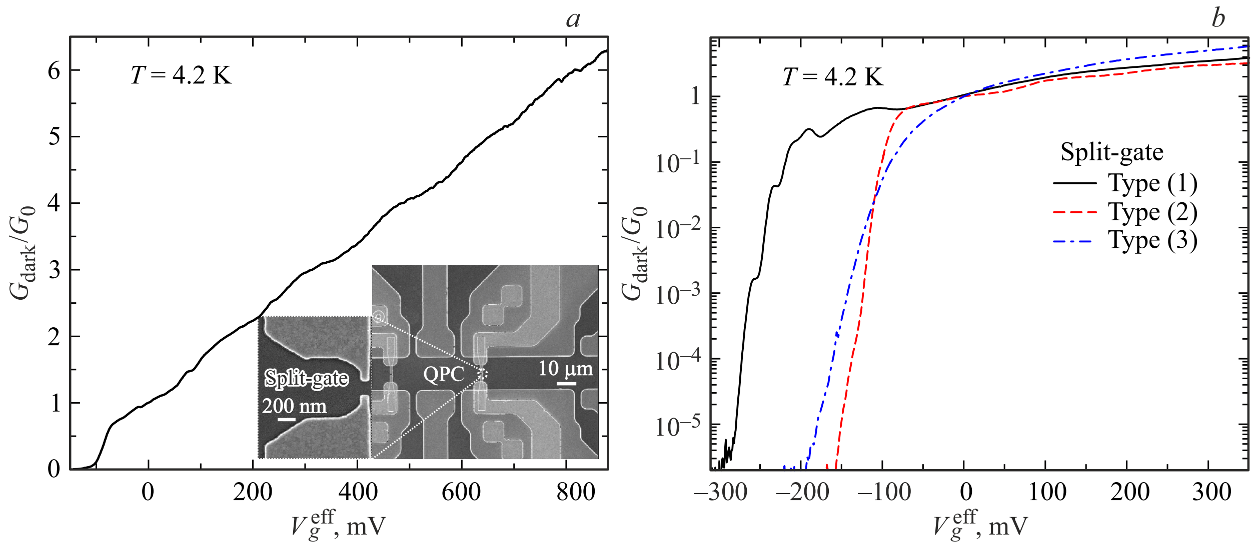

Figure 2. *a*) — dark conductance G_{dark}/G_0 of QPC vs. gate voltage V_g^{eff} in open mode (inset — electronic image of QPC), *b*) — dependencies $G_{dark}(V_g^{eff})/G_0$ for three types of QPC in tunnel mode and during transition from this mode to open one.

based on single heterojunctions (HJ) with δ-doping layers in AlGaAs (Figure 3, *a*) and with a complex structure of doping layers in AlGaAs (Figure 3, *b*). The main and important difference is that during the transition from the tunnel mode to the open one G_{ph} of QPC based on δ-doped HJs does not change sign, whereas the photoconductance of QPCs based on HJs with complex layer structure changes sign just in the vicinity of $G \approx 0.5G_0$: at $G > 0.5G_0$ the sign of the photoconductance becomes negative. The photoconductance of QPC based on quantum well (Figure 3, *c*) also changes sign, but at a higher value $G \approx G_0$. Note that presence of a kind of critical point — the change in the sign of photoconductance occurs at approximately the same conductance value, regardless of the radiation power. The presented results also allow us to conclude that there are no overheating effects in the behavior of microwave photoconductance, since its sign is simply opposite to the sign of the change in conductance, which should follow from the temperature dependence of dark conductance. The overheating effects were also evaluated on the basis of a comparative analysis of the temperature dependence of the conductivity of two-dimensional electron gas and the microwave photoconductivity of this gas under the assumption that this PC is due the heating effect only. Evaluation gives overheating by tenths of a degree, i. e., it is negligible in comparison with the experimental temperature.

Let us now discuss the results described above on the basis of the theory of microwave photoconductance, presented in the paper [10], and in which its occurrence was first reported. This theory provided almost complete explanation of the basic properties of the microwave response of QPC studied in [10] and made it possible to determine the main mechanism of the influence of microwave radiation associated with the fact that the microwave photoconductance of the QPC during the adiabatic passage of electron through it ($\omega\tau \ll 1$, $\omega = 2\pi f$, τ — tunneling time) is determined by forced oscillations of the saddle point potential and measuring voltage in a wide range of conductance values ($10^{-4}G_0 < G < 3G_0$), i. e., including both tunnel and open modes. Within the framework of the basic formulas of the theory under discussion, the change in the sign of the PC during the transition from the tunnel to the open mode is not necessary, but is caused by a parameter that is free in this theory, i. e. the ratio of the amplitude δV of forced oscillations of the measuring voltage to the amplitude A of forced oscillations of the saddle point potential. The proportionality $\delta V \propto A$ is obvious, but the sign of the proportionality coefficient between them is not obvious without comparing theory with experiment. It is only clear that the microwave-induced charges on all conductive parts of the sample at any time have the same sign, but the difference in the densities of these charges on the potentiometric contacts at a given moment can have one or another sign, and after 1/2 period this the sign will become opposite, and the same is applied to the induced measuring voltage on the potentiometric contacts. The sign of the microwave-induced voltages on the gate $\Delta V_g \cos(\omega t)$ and between the potentiometric contacts $\delta V \cos(\omega t)$ can be the same or different, i. e. forced oscillations of these two values can be in-phase or anti-phase. The implementation of any of these possibilities probably depends on the structure of the basic heterostructure and the geometry of the mesoscopic system with QPC. In [10] the sign of the proportionality coefficient in $\delta V \propto A$ is taken positive to explain the experiments with QPC performed at that time. Figure 4, *a* shows the calculated dependences of the time-averaged $\langle D \rangle$ — coefficient of electron transmission through the QPC, which determines the conductance without taking into account forced oscillations of the measuring voltage. In this case, a negative PC does not appear at the exit to the

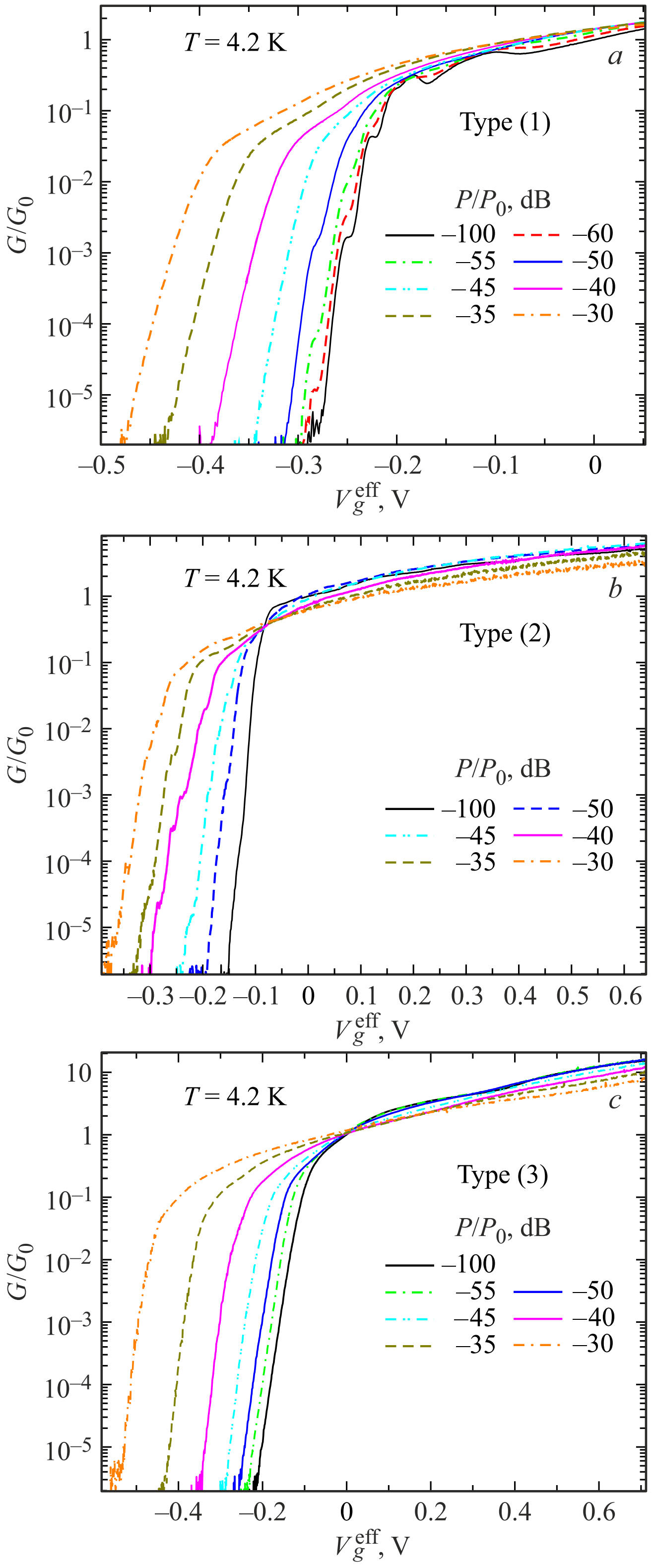

Figure 3. Dependence of gate voltage $G(V_g^{eff})/G_0$ at $T = 4.2$ K for series of microwave power P/P_0 for QPC: *a*) based on single heterojunctions with doping δ-layers in AlGaAs, *b*) based on single heterojunctions with complex superlattice structure of doping layers in AlGaAs, *c*) based on heterojunction with GaAs quantum well.

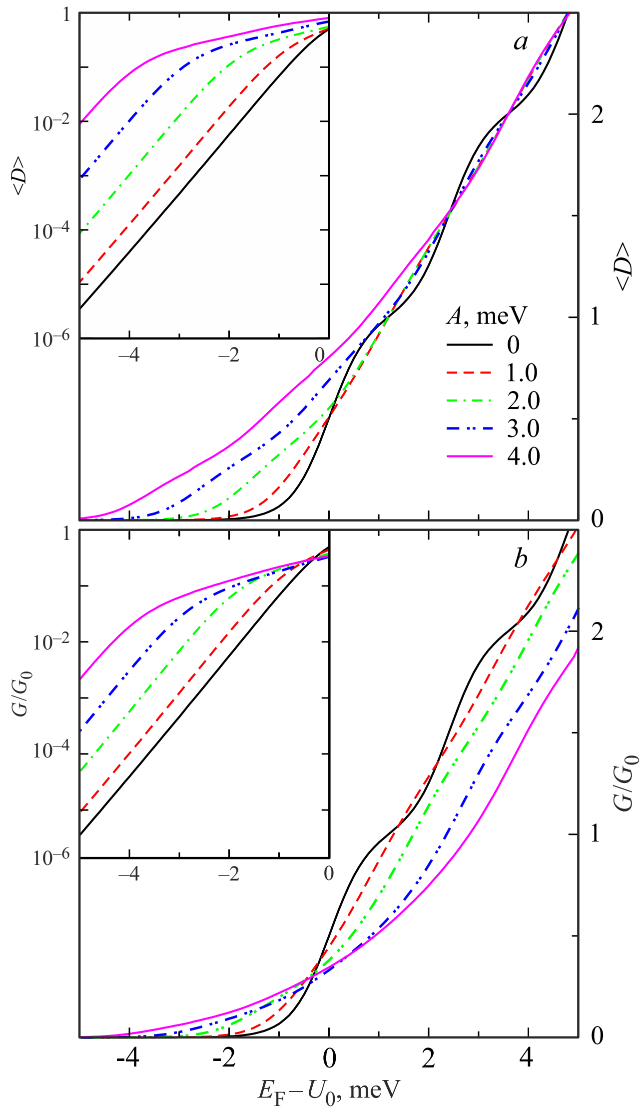

Figure 4. Calculated dependences $\langle D\rangle$ and G/G_0 from $E_F - U_0$ at $T = 0$ for series of values A — amplitude of forced oscillations of saddle point potential of QPC: *a*) — not considering forced oscillations of measuring voltage, and *b*) — considering this at $\delta V/A > 0$.

open mode. For comparison, the result of calculations of the QPC conductance used in [10] is shown, taking into account oscillations of the measuring voltage at $\delta V/A > 0$ (Figure 4, *b*). In this case, the addition to $\langle D\rangle$ is negative, and the conductance everywhere decreases with increase in A, which leads to negative PC upon transition to the open mode. It is obvious, however, that at $\delta V/A < 0$ the addition to $\langle D\rangle$ will become positive, and PC will remain positive everywhere in the considered range of the parameter $E_F - U_0$, which linearly depends on the effective gate voltage. The change in PC sign for this formal reason does not contradict the detected behavior of the PC of quantum point contacts based on various heterostructures (Figure 3).

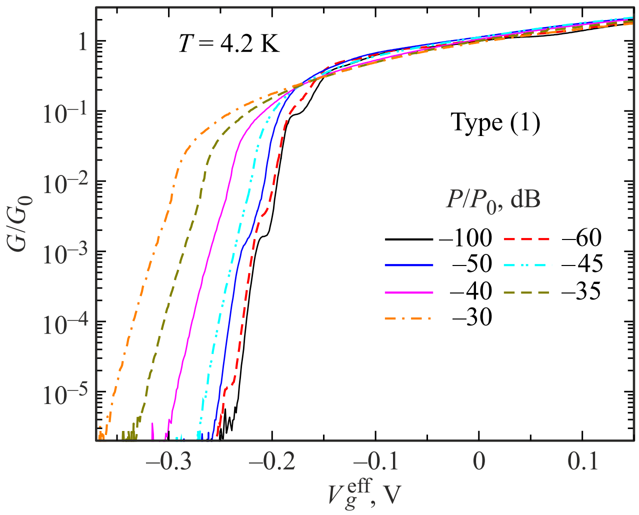

Figure 5. Dependence of conductance $G(V_g^{eff})/G_0$ for series of values of microwave power P/P_0 for QPC manufactured based on AlGaAs/GaAs single heterojunction with two δ-layers of silicon in AlGaAs, measured at one of other immersions of sample in liquid helium.

In the theory [10] for simplicity the assumption was used that the two-dimensional potential in QPC allows for the separation of variables in the Schrödinger equation, that the transverse potential is a parabola, and the longitudinal potential is an Eckart potential. Of course, under these assumptions, the QPC conductance is a smooth function of the gate voltage (Figure 4). This did not contradict the results of studying samples in [10]. However, the currently discovered steps in the tunnel mode shown in Figures 1–3, 5 indicate that the usual assumptions of simple theory do not take into account the actual shape of the two-dimensional potential in the quantum point contact, and this is one of the objects of study of mesoscopic transport and disorder, and at that the impurity disorder plays an important role.

Moreover, an interesting fact was discovered indicating that the response of actual QPC to microwave radiation is not uniquely determined by the heterostructure and geometry of the conducting parts of the device. Figure 5 shows the dependences $G(V_g^{eff})$ for QPC sample, the photoconductance behavior of which is shown in Figure 3, *a*, but measured during a different immersion in helium. It is clearly seen that if after the first immersion there is no change in the PC sign (Figure 3, *a*), then after another immersion it appears. According to the proposed theory, this behavior can be associated with the fact that the charge state of the impurity system affects the sign of the amplitude of forced oscillations of the measuring voltage by analogy with the known sign-alternating frequency response of the photo-EMF of other mesoscopic systems in semiconductor two-dimensional electron gas. In turn, the charge state of the impurities depends on the procedure for cooling the sample with the QPC, which can be different in each experiment due to various random reasons (humidity in the experimental room, cooling time, different thermal conductivity of the sample holder, etc.). The different state of the entire impurity system can obviously affect the shape of the two-dimensional potential in the actual sample with QPC and the sign of the amplitude of the measuring voltage. Probably, just this reason is indicated by the results of the experiment in Figures 3, 5, and the absence or presence of change in the sign of the PC can be explained within the framework of the basic formulas of the theory, which is illustrated here by Figure 4.

Thus, the experiments carried out in this paper show that the behavior of the conductance and microwave photoconductance of QPCs based on two-dimensional electron gas in GaAs heterojunctions and quantum wells is not described in terms of the idealized Eckart potential [10], but also depends on the charge state and structures of doping layers in AlGaAs barriers.

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Conflict of interest

The author declares that he has no conflict of interest.

References

[1] B.J. van Wees, H. van Houten, C.W.J. Beenakker, J.G. Williamson, L.P. Kouwenhoven, D. van der Marel, C.T. Foxon. Phys. Rev. Lett. **60**, 848 (1988).
[2] D. Wharam, T.J. Thornton, R. Newbury, M. Pepper, H. Ahmed, J.E.F. Frost, D.G. Hasko, D.C. Peacock, D.A. Ritchie, G.A.C. Jones. J. Phys. C **21**, L209 (1988).
[3] Mesoscopic Phenomena in Solids / Ed. B.L. Altshuler, P.A. Lee, R.A. Webb. North-Holland, Amsterdam (1991).
[4] M.Büttiker. Semicond. Semimet. **35**, 191 (1992).
[5] Mesoscopic Electron Transport / Ed. L. Sohn, L.P. Kouwenhoven, G. Schön. Kluwer, Dordrecht (1997).
[6] O.A. Tkachenko, V.A. Tkachenko, Z.D. Kvon, A.V. Latyshev, A.L. Aseev. Nanotechnol. Russ. **5**, 676 (2010).
[7] N.M. Shchelkachev, Ya.V. Fominov. Electric Current in Nanostructures: Coulomb Blockade and Quantum Point Contacts, Study Guide (MFTI, Moscow, 2010). (in Russian)
[8] A.D. Levin, G.M. Gusev, Z.D. Kvon, A.K. Bakarov, N.A. Savostianova, S.A. Mikhailov, E.E. Rodyakina, A.V. Latyshev. Appl. Phys. Lett. **107**, 072112 (2015).
[9] M. Otteneder, Z.D. Kvon, O.A. Tkachenko, V.A. Tkachenko, A.S. Jaroshevich, E.E. Rodyakina, A.V. Latyshev, S.D. Ganichev. Phys. Rev. Appl. **10**, 014015 (2018).
[10] V.A. Tkachenko, A.S. Yaroshevich, Z.D. Kvon, O.A. Tkachenko, E.E. Rodyakina, A.V. Latyshev. JETP Lett. **114**, 110 (2021).
[11] M. Otteneder, M. Hild, Z.D. Kvon, E.E. Rodyakina, M.M. Glazov, S.D. Ganichev. Phys. Rev. B **104**, 205304 (2021).

[12] A.H. Dayem, R.J. Martin. Phys. Rev. Lett. **8**, 246 (1962).
[13] P.K. Tien, J.P. Gordon. Phys. Rev. **129**, 647 (1963).
[14] V.A. Chitta, R.E.M. de Bekker, J.C. Maan, S.J. Hawksworth, J.M. Chamberlain, M. Henini, G. Hill. Semicond. Sci. Technol. **7**, 432 (1992).
[15] P.S.S. Guimarães, B.J. Keay, J.P. Kaminski, S.J. Allen Jr., P.F. Hopkins, A.C. Gossard, L.T. Florez, J.P. Harbison. Phys. Rev. Lett. **70**, 3792 (1993).
[16] H. Drexler, J.S. Scott, S.J. Allen, K.L. Campman, A.C. Gossard. Appl. Phys. Lett. **67**, 2816 (1995).
[17] D.D. Coon, H.C. Liu. J. Appl. Phys. **58**, 2230 (1985).
[18] D. Sokolovski. Phys. Rev. B **37**, 4201 (1988).
[19] R.A. Sacks, A. Szoke. Phys. Rev. A **40**, 5614 (1989).
[20] M.Yu. Sumetskii, M.L. Fel'shtyn. JETP Lett. 53, 24 (1991)
[21] M.J. Hagmann. J. Appl. Phys. **78**, 25 (1995).
[22] M. Büttiker, R. Landauer. Phys. Rev. Lett. **49**, 1739 (1982).
[23] C. Eckart. Phys. Rev. **35**, 1303 (1930).
[24] L.D. Landau and E.M. Lifshitz, Course of Theoretical Physics, Vol. 3: Quantum Mechanics: Non-Relativistic Theory (Nauka, Moscow, 1989; Pergamon, New York, 1977).
[25] O.A. Tkachenko, V.A. Tkachenko, Z.D. Kvon. JETP Lett. **102**, 378 (2015).
[26] O.A. Tkachenko, V.A. Tkachenko, D.G. Baksheev. Sibirskij fiz. zhurn.. **13**, *4*, 74 (2018). (in Russian).
[27] V.A. Tkachenko, Z.D. Kvon, O.A. Tkachenko, A.S. Yaroshevich, E.E. Rodyakina, D.G. Baksheev, A.V. Latyshev. JETP Lett. **113**, 331 (2021).

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