UDC 621.315.592

# Photo-voltaic effect in 2DEG of lateral superlattices in uniform magnetic field at the lack of inversion symmetry

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Received April 19, 2024
Revised September 19, 2024
Accepted September 19, 2024

The energy spectrum of an electron in the periodic electrostatic field of a surface superlattice and in a sufficiently strong perpendicular uniform magnetic field consist of narrow minibands formed near Landau levels. The electron Hamiltonian commutes with the magnetic translation operator, and the magnetic field is assumed to be such that the elementary cell of the superlattice is permeated by a magnetic flux equal to a rational number of its quanta. According to Kramers' theorem, in an external magnetic field, the electron dispersion laws are not even functions of quasimomentum projections if the periodic potential of the superlattice field does not have an inversion center $V(\mathbf{r}) \neq V(-\mathbf{r})$. Therefore, when carriers transition under the action of an electromagnet wave of a certain polarization from occupied magnetic subband to an free one, a non-zero surface electric current occurs in the system. The paper presents model calculations of the density of such a surface current for typical and experimentally realized parameters of superlattices. Depending on the parameters determining the degree of violation of the spatial inversion symmetry of the superlattice, the vector of the surface electron current density can change direction.

**Keywords:** Photo-voltatic effect, semiconductor superlattices.

DOI: 10.61011/SC.2024.07.59538.6327H

## 1. Introduction

The superlattices are commonly referred to as the solid-state structures where, apart form the lattice periodic potential, there's an additional artificial periodicity of electrostatic field with a period significantly outpacing the lattice constant. The two-dimensional (lateral) superlattices are obtained when the surface charge plane is periodically modulated in the charge carriers layer [1]. The superlattices created by the electron lithography are preferred in terms of magnetotransport and magnetooptical experiments, first of all, due to a high degree of their periodicity [2,3]. It is also possible to create the superlattices with a various symmetry of the lattice cell, disrupt the inversion symmetry, building a two-dimensional acentric artificial crystal. When applying the external magnetic field, perpendicular to the carriers gas plane, the laws of dispersion of the charge carriers in the magnetic Bloch sub-bands will not represent the even functions of quasi-pulse any longer.

The range of the materials used to theoretically and experimentally study the photovoltaic effects in gas of the charge carriers is quite wide. Thus, paper [4] provides a calculated dependence of the photo-galvanic current from parameters of the superlattice consisting of periodically arranged 1D rectangular wells and barriers. In straight transitions between the mini-bands of the conduction band a photocurrent occurred. Paper [5] outlines the study of photovoltaic effect in 1D asymmetric superlattices placed in magnetic field. In study [6] a magneto-photovoltaic effect was observed associated with the structures gyrotropy and arising from the inter-subband transitions in GaAs quantum wells with orientation [001]. It is shown that the inter-subband absorption of linearly polarized radiation can lead to both spin-dependent and spin-independent photocurrents if an external magnetic field is applied in the plane of the quantum well. The asymmetric graphene superlattices [7] allow generating the ratchet photocurrents when absorbing normally incident electromagnetic radiation, and experiments were made in graphene-based 2D-metamaterials with development of the phenomenological and microscopic ratchet effects theories for a system irradiated by a terahertz electromagnetic wave [8,9]. The metamaterial is a graphite gate with an array of periodically arranged triangular antidots placed under a graphene monolayer. The ratchet current in the carrier gas arises because of the non-centrosymmetric lattice cell of the periodic structure and is generated due to the combined action of a spatially periodic planar electrostatic potential and a periodically modulated electric radiation field under conditions of intra-band absorption. It was shown that the fermionic system with a linear dispersion law converts the AC current into the DC current in case of a spatial asymmetry [9]. This effect is controllable and the ratchet current changes its direction into the opposite one when switching the radiation helicity. The experiment was conducted at room temperature and a radiation frequency of 2.54 THz, and the results were analyzed in accordance with the developed microscopic theory, providing for the electronic and plasmonic mechanisms of ratchet current formation.

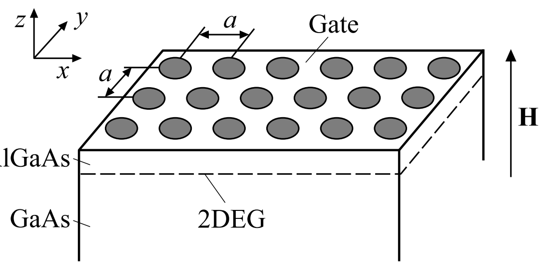


**Figure 1.** Diagram of the semiconductor heterojunction with a surface superlattice, which is placed in the perpendicular magnetic field **H**.

Our study is focused on a layer of two-dimensional electrons in AlGaAs/GaAs heterojunction with a surface superlattice that was placed in a uniform magnetic field perpendicular to the carriers gas. The model diagram of the heterojunction is shown in Figure 1. The technology for creating such structures with a control metal gate in the immediate vicinity of the heterointerface boundary was developed earlier in papers [2,3].

In this paper, the quantum states of charge carriers are calculated for a case when the periodic potential of the superlattice does not have a center of spatial inversion. In a two-dimensional electron gas of such a system, a photovoltaic effect occurs during single-photon direct junctions in the spectrum under the action of an electromagnetic wave. The surface density of the occurring current is calculated. All calculations represent a model analysis and are carried out for the experimentally proven superlattice parameters and magnetic field intensities. The crystallographic directions in GaAs were neglected in the study. Zero temperature was taken in calculations. Naturally, in conditions of in-situ experiments with an electron gas, scattering processes are pivotal in magneto-optical and magneto-transport effects. Thus, the longitudinal acoustic phonons generate a deformation potential (DA-scattering) for the charge carriers. It is important to note that a piezoelectric scattering (PA-scattering) existing independent of the deformation-acoustic scattering is typical for crystals with a zinc blende structure, while the piezopotenial for the electrons in Γ-valley is created both by the transverse and longitudinal phonons [10]. At the same time, the pulse relaxation of the charge carriers at the low temperatures is mainly determined, of course, by elastic scattering on the impurity ions and the neutral atoms. It can be expected that at temperatures of several tens of millikelvins, the energy uncertainty in sufficiently pure samples with a carrier pulse relaxation time of about a hundred picoseconds will not lead to a significant blurring of the carriers' energy mini-bands.

## 2. Quantum states of the charge carriers

Hamilton describing the quantum-mechanical motion of electron in the considered system look as $\widehat{H} = \widehat{H}_0 + V(x,y)\widehat{E}$, where $\widehat{H}_0$ — Hamiltonian of the electron in constant uniform magnetic field, $\widehat{E}$ — unit operator. A model of the non-centrosymmetric potential of the electrostatic field of a superlattice has been reviewed, when the potential energy of an electron in the periodic electrostatic field of a superlattice (two-dimensional artificial crystal) is expressed as

$$V(x,y) = V_0\big(\cos^2(\pi x/a)\cdot\cos^2(\pi y/a) + \cos^2(\pi(x-d_x)/a)\cdot\cos^2(\pi(y-d_y)/a)\big). \quad (1)$$

The electrostatic potential (1) has a periodic nature in space with a period of $a$ and totally delineates the fundamental properties of the carriers electronic spectrum in the absence of a spatial inversion center at non-zero displacement vector $\mathbf{d} = \{d_x, d_y\}$. The choice of a specific expression for model calculations depends only on potential use of existing technologies for manufacturing two-dimensional superlattices. With displacements $d_x = d_y = 0$ in expression (1) the inversion symmetry of the potential is restored (Figure 2).

For parameters of the up-to-date semiconductor superlattices with a period 50−80 nm and magnetic field strengths of about several tens of thousands of Oersteds, the typical splitting in the carrier spectrum due to the action of the superlattice electrostatic field on the electron turns out to be much less than the typical Landau energy $\hbar\omega_C$. That is why it is possible to perform the model analysis of the electron quantum states in a single-level approximation, when it is possible to neglect the impurity of the Landau neighboring states in the states of magnetic Bloch sub-bands of this energy level $E_N = \hbar\omega_C(N + 1/2)$ with the given value of number $N$. Besides, as the typical period of the superlattices of several dozens of nanometers exceeds by two orders the scale of natural periodicity of the crystal, it is justified to use an approximation of the isotropic effective mass in Γ-point.

In terms of irreducible projective representations of magnetic translations group the electrons quantum states may be classified only when magnetic flux passing through the superlattice cell (measured in flux quanta $\Phi_0$) is a rational number $p/q = |e|Ha^2/2\pi\hbar c$ [11]. Then, the wave function of electron in $\mu$-th magnetic sub-band ($\mu = 1, p$), which at the same time is an eigen function of magnetic translation operator, is expressed as follows

$$\Psi^{\mu}_{\mathbf{k}} = \sum_{N=0}^{\infty}\sum_{n=1}^{p} C^{\mu}_{Nn}(\mathbf{k}) \sum_{l=-\infty}^{+\infty} \exp(ik_x a(lq + nq/p) + 2\pi i y(lp+n)/a)\cdot\exp(ik_y y) \times \varphi_N\big((x - x_0 - lqa - nqa/p)/l_H\big) \quad (2)$$

and is represented by the symmetrized linear combination of Landau basis states $\varphi_N$ in constant magnetic field ($l_H$ — magnetic length). Thus, functions (2) form $p$-dimensional delamination above a 2D torus — Brillouin magnetic zone (BMZ): $-\pi/qa \le k_x \le \pi/qa$, $-\pi/a \le k_y \le \pi/a$.

The stationary Schrodinger equation was solved numerically using the method of unitary transformations of

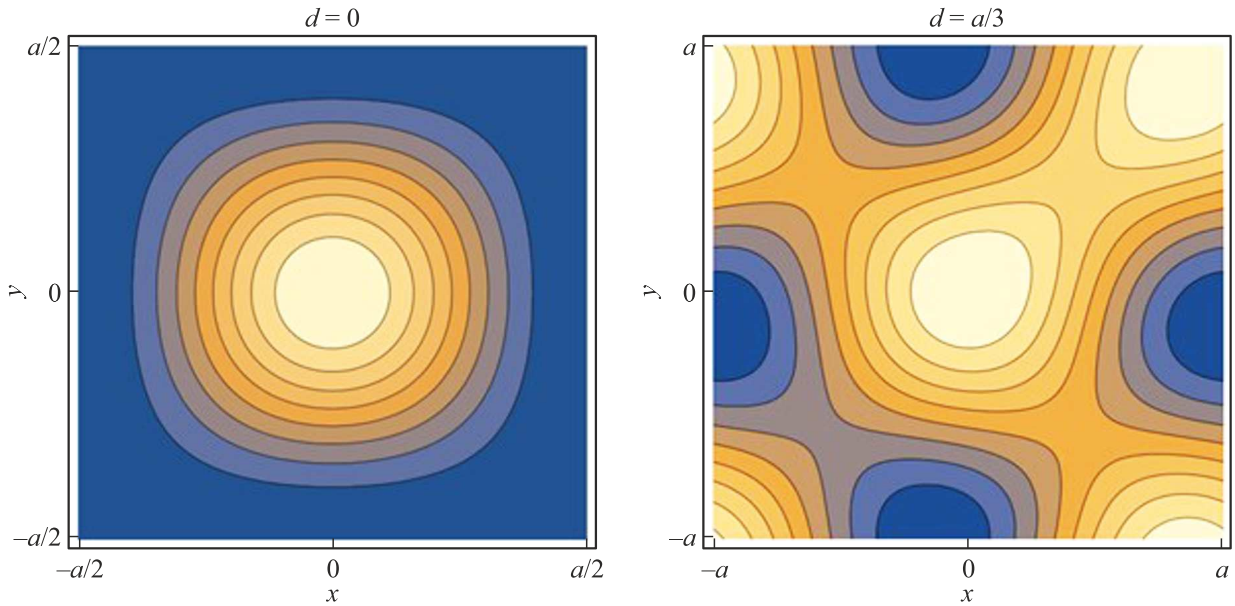


**Figure 2.** Equipotential lines of potential (1) for the two values of displacements $d_x = d_y = d$. At $d \neq 0$ the inversion center in the superlattice cell is absent.

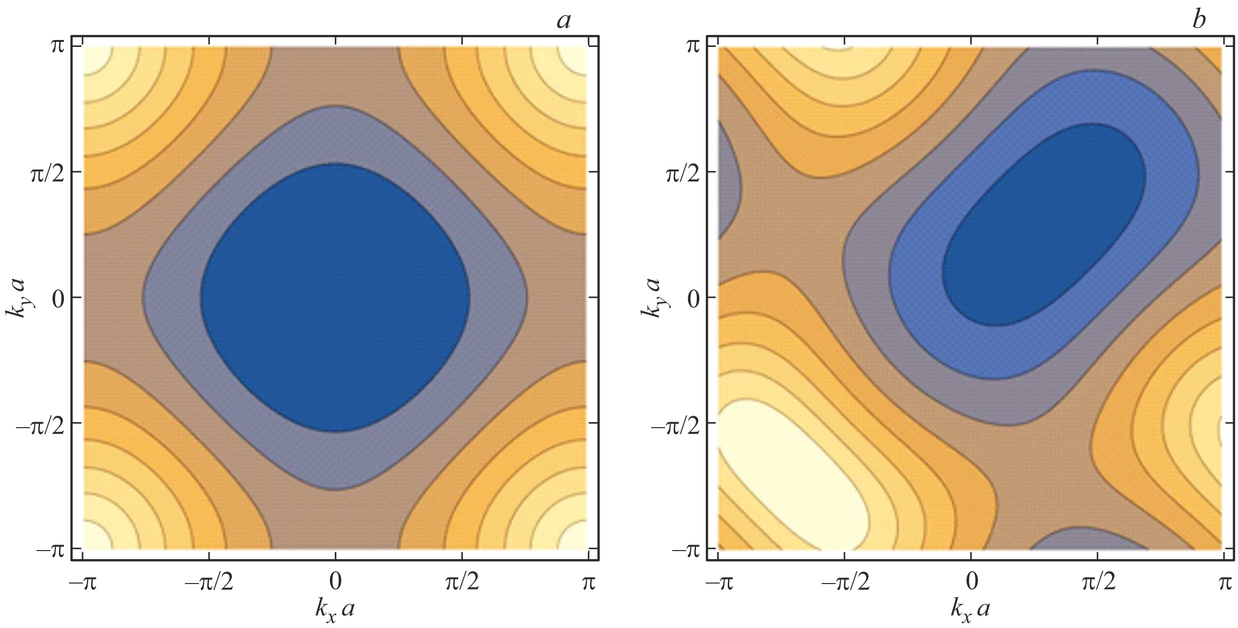


**Figure 3.** The isoenergetic levels in the lowest magnetic sub-band related to the main Landau level at $p/q = 4/1$ in AlGaAs/GaAs model structure with parameters: $V_0 = 1\,$MeV, $m^* = 0.067m_0$, $a = 50\,$nm; $a$ — $d = 0$, $b$ — $d_{x,y} = d = a/3$. The darker areas in the Figure correspond to the lower carrier energies.

the basis for diagonalization of the Hamiltonian matrix. In expression (2) five Landau levels were taken into account, and the number of quanta of the magnetic flux through the unit cell of the superlattice varied from 3 to 5, taking, among other things, non-integer values. The calculated parameters of the model were taken corresponding to their actual values in experiments with two-dimensional electron gas of the surface superlattices. Thus, the superlattice period $a$ was taken equal 50 nm, and amplitude of periodic potential $V_0 = 1\,$meV, the module of magnetic field intensity with the above-mentioned period and magnetic flux quanta number $p/q = 4/1$ is approximately equal $H \approx 6.63 \cdot 10^4\,$E. At that, the width of the split band structure of a separate Landau level (magnitude of $V_0 = 1\,$MeV) is much less than the characteristic cyclotron energy $\hbar\omega_C = 2\pi\hbar^2 p/m^* a^2 q \approx 11.45\,$MeV.

Figure 3 illustrates the calculated laws of dispersion (isoenergetic lines) of carriers in the lower magnetic sub-

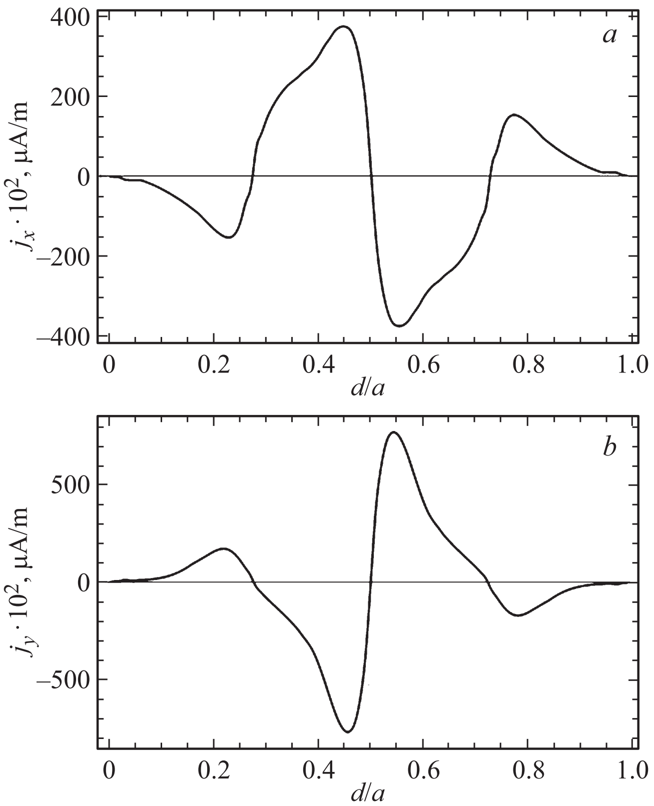


**Figure 4.** Surface current density projections (4) versus ratio $d_{x,y}/a$ at $d_x = d_y$, $V_0 = 1$ MeV, $a = 50$ nm, $p/q = 4/1$: $a$ — $j_x^{15}$, $b$ — $j_y^{15}$. Junctions from the zero level main magnetic sub-band into the lowest sub-band ($\mu = 5$) of Landau first level.

band of the Landau zero level with the number of magnetic flux quanta $p/q = 4/1$. Since the model periodic potential of the superlattice has no inversion center at $d_{x,y} \neq 0$, $a/2$, then as per Kramers theorem, in the magnetic field the sub-band electron dispersion laws are not the even functions of quasi-pulse projections in BMZ (Figure 3, $b$).

## 3. Photovoltaic effect in 2D electron gas

In the absence of symmetry of the energy spectrum in **k**-space, a photovoltaic effect should be observed in a variable electromagnetic field — a flow of dc current in a heterojunction irradiated by an electromagnetic wave propagating perpendicular to the surface of the structure. In the considered model of the non-centrosymmetric potential of a superlattice in magnetic field, during transitions in the carrier spectrum with photon absorption, the electron group velocities at various mirror-symmetric BMZ points are not opposite to each other, and as a result, an uncompensated electron photocurrent occurs in the energy subzone of finite states. The model control parameters are $d_{x,y}$ displacements, which when zeroed, result in the potential restoring its inversion symmetry. The effect of an electromagnetic wave on an electron was taken into account by us according to the theory of perturbations. The wave was assumed to be linearly polarized in $x$ direction and propagating perpendicular to the gas carriers plane. In significantly strong magnetic field ($V_0/\hbar\omega_C \ll 1$) the magnetic sub-bands have good resolution in terms of energy and can be attributed to the Landau level. Direct transitions in the spectrum are most likely between sub-bands of neighboring Landau levels, since the wave is linearly polarized. The constant magnetic field was taken such that the number of quanta of the magnetic flux through the superlattice unit cell becomes rational $p/q = 4/1$. The effective mass $m^*$ of electron in GaAs was taken equal $0.067m_e$, lattice period $a = 50$ nm. Fermi level has such a position, that the lowest magnetic sub-band ($\mu = 1$) of Landau main level is filled. This corresponds to the carriers concentrations of $n = 0.8 \cdot 10^{11}\,\text{cm}^{-2}$. In our paper we've obtained the analytic expression for the square module of the matrix element transition between the states (initial $i$ and final $f$) of magnetic sub-bands for the case of linear polarized electromagnetic waves absorption:

$$\left|M_{\mathbf{kk}}^{i\to f}\right|^2 = \frac{e^2\hbar^2 A_w^2}{2(qam_0cl_H)^2}\left|\sum_{N=0}^{\infty}\sum_{n,s=1}^{p} C_{N-1,s}^{f*}(\mathbf{k})C_{N,n}^{i}(\mathbf{k})\sqrt{N} + C_{N+1,s}^{f*}(\mathbf{k})C_{N,n}^{i}(\mathbf{k})\sqrt{N+1}\right|^2, \quad (3)$$

where $m_0$ — mass of a free electron, $A_w$ — amplitude of the vector potential of the electromagnetic field wave, which in the analysis corresponded to the experimental value of the wave field energy flow density at single-photon junctions $10\,\text{MW/cm}^2$. Prior to calculate the surface density of the current occurring during transitions from

$$\mathbf{j}^{\mu} = (2e/h)\int \mathbf{v}^{\mu}\left|M^{1\to\mu}\right|^2 dk_x dk_y \quad (4)$$

the first (main) to the free $\mu$-th magnetic sub-band of the neighboring (first) Landau level the field of group velocities $\mathbf{v}^{\mu}$ has been calculated.

Figure 4 shows the results of calculation of $x$- and $y$-projections of the surface current in conditions of photovoltaic effect occurrence in the studied model structures. The transitions in the spectrum are most intense between the main magnetic sub-band of zero energy level in magnetic field and the lower magnetic sub-band belonging to the first Landau level. Depending on the magnitude of the ratio of $d_{x,y}$ to the superlattice period, the current density projection changes its sign because the carriers group velocities field projections determined by the law of dispersion change their sign. When the super-lattice field potential is centrosymmetric ($V(\mathbf{r}) = V(-\mathbf{r})$), the current density vector is zero, and there's no photovoltaic effect in the carriers gas. The calculated value of the surface current corresponds to the absorption of a wave by a single layer of two-dimensional electrons. In a multilayer structure, one can expect an amplification of the effect, which generally non-linearly depends on the number of carrier gas layers.

## 4. Conclusion

Two-dimensional semiconductor superlattices placed in a constant magnetic field are an example of solid-state artificial periodic structures with a non-trivial energy spectrum of charge carriers. Removal of degeneracy along the center of the orbit in a magnetic field because of the superlattice periodic electrostatic field results in formation of magnetic mini-bands, and it is no longer necessary to talk about the existence of a „staircase“ of infinitely thin Landau levels for electrons. In the absence of a center of spatial inversion of artificially created periodicity, a constant surface current may occur in such structures when they are irradiated with an electromagnetic wave of the far-long infrared or microwave bands. Thus, such semiconductor structures become another object where a photovoltaic effect can occur in the carrier gas. The photovoltaic effect calculated in this paper is a controlled effect. In our model analysis, the magnitude and direction of the emerging DC current can be controlled by changing the magnitude of the constant magnetic field strength, as well as by varying the parameters of a two-dimensional superlattice. Meanwhile, the issue of the effect experimental control technologies is still unresolved. It can be expected that in any semiconductor planar superlattices with broken spatial inversion symmetry, this effect will take place, and its experimental study will become possible.

### Funding

This study was supported by the Ministry of Science and Higher Education of the RF under State Assignment No. FSWR-2023-0035.

### Conflict of interest

The authors declare that they have no conflict of interest.

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*Translated by T.Zorina*