

Heterostructures, superlattices, quantum wells

Conference materials

UDC 538.9

DOI: <https://doi.org/10.18721/JPM.161.311>

Magneto-intersubband resistance oscillations in a one-dimensional lateral superlattice

I.S. Strygin¹ ✉, A.A. Bykov¹

¹Rzhanov Institute of Semiconductor Physics, Siberian Branch, RAS, Novosibirsk, Russian

✉ vanya-91@yandex.ru

Abstract. This paper presents the results of a study of magneto-intersubband resistance oscillations in a one-dimensional lateral superlattice fabricated on the basis of a single GaAs quantum well with two filled energy subbands. A strong modification of magneto-intersubband oscillations both in amplitude and in phase has been observed. The obtained experimental data are explained by the role of Van Hove singularities in resonant intersubband transitions.

Keywords: magneto-intersubband oscillations, lateral superlattice

Funding: This study was funded by the Russian Science Foundation grant number RSF-22-22-00726, <https://rscf.ru/en/project/22-22-00726/>.

Citation: Strygin I.S., Bykov A.A., Magneto-intersubband resistance oscillations in a one-dimensional lateral superlattice, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.3) (2023) 67–72. DOI: <https://doi.org/10.18721/JPM.161.311>

This is an open access article under the CC BY-NC 4.0 license (<https://creativecommons.org/licenses/by-nc/4.0/>)

Материалы конференции

УДК 538.9

DOI: <https://doi.org/10.18721/JPM.161.311>

Магнито-межподзонные осцилляции сопротивления в одномерной латеральной сверхрешетке

И.С. Стрыгин¹ ✉, А.А. Быков¹

¹Институт физики полупроводников им. А. В. Ржанова Сибирского отделения РАН,

г. Новосибирск, Россия

✉ vanya-91@yandex.ru

Аннотация. В работе приводятся результаты исследования магнито-межподзонных осцилляций сопротивления в одномерной латеральной сверхрешетке, изготовленной на основе одиночной GaAs квантовой ямы с двумя заполненными энергетическими подзонами. Обнаружена сильная модификация магнито-межподзонных осцилляций по амплитуде и фазе. Полученные экспериментальные данные объясняются ролью особенностей Ван Хофа в резонансных межподзонных переходах.

Ключевые слова: магнито-межподзонные осцилляции, латеральная сверхрешетка

Финансирование: Исследование выполнено за счет гранта Российского научного фонда номер РНФ-22-22-00726, <https://rscf.ru/project/22-22-00726/>.

Ссылка при цитировании: Стрыгин И.С., Быков А.А. Магнито-межподзонные осцилляции сопротивления в одномерной латеральной сверхрешетке // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.3. С. 67–72. DOI: <https://doi.org/10.18721/JPM.161.311>

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (<https://creativecommons.org/licenses/by-nc/4.0/>)

Introduction

Landau quantization in quasi-two-dimensional electronic systems in which several size-quantization subbands E_j are filled (j is the subband index) leads not only to several series of Shubnikov-de Haas (SdH) oscillations, but also to magneto-intersubband resistance oscillations (MISO) of ρ_{xx} versus magnetic field B [1]. The MISO are due to elastic intersubband scattering, which becomes resonant when the Landau levels of different subbands coincide. In a two-subband system with a large number of filled and strongly overlapping Landau levels, MISO are described by the following relation [2]:

$$\Delta\rho_{\text{MISO}} / \rho_0 = A_{\text{MISO}} \exp\left(-2\pi / \omega_c \tau_q^{\text{MISO}}\right) \cos\left(2\pi\Delta_{12} / \hbar\omega_c\right), \quad (1)$$

where $\rho_0 = \rho_{xx}(B=0)$, $A_{\text{MISO}} = 2\tau_{tr}/\tau_{12}$, τ_{tr} is the transport scattering time, τ_{12} is the intersubband scattering time, $\tau^{\text{MISO}} = 2\tau_{q1}\tau_{q2}/(\tau_{q1} + \tau_{q2})$, τ_{qj} is the quantum lifetime, Δ_{12} is the intersubband splitting, $\omega_c = eB/m^*$ is the cyclotron frequency, and m^* is the electron effective mass. MISO are not suppressed by temperature broadening of the Fermi distribution function, which makes it possible to use them to study quantum transport under conditions when SdH oscillations are suppressed [3].

This work considers MISO in a two-subband unidirectional lateral superlattice (ULSL), a quasi-two-dimensional electron system with one-dimensional periodic potential modulation: $V(x) = V_0 \cos(2\pi x/a)$, where V_0 is the potential amplitude and a is the modulation period. The most striking phenomenon found in the ULSL is the commensurate oscillations (CO) of the resistance [4]. The maxima and minima of CO occur when the following conditions are satisfied:

$$2R_{cj}/a = (i + 1/4), \quad (2)$$

$$2R_{cj}/a = (i - 1/4), \quad (3)$$

where R_{cj} is the cyclotron radius and i is a positive integer. Within the framework of the classical model, COs arise due to the commensurability between R_{cj} and a [5], and within the framework of the quantum mechanical model they result from a periodic change in the width of the Landau bands with $1/B$ [6].

The one-dimensional periodic potential removes the degeneracy of the Landau levels with respect to the coordinate of the center of the wave function x_0 , which leads to the formation of Landau bands. Under the conditions $V_0 \ll E_F - E_j = \varepsilon_{Fj}$ (E_F is the position of the Fermi level), the dependence of the Landau level E_{N_j} with $N_j \gg 1$ on x_0 is given by the expression [6]:

$$E_{N_j}(x_0) \approx E_j + (N_j + 1/2)\hbar\omega_c + V_{Bj} \cos(2\pi x_0/a), \quad (4)$$

$$V_{Bj} = V_0 J_0(2\pi R_{cj}/a). \quad (5)$$

For $2\pi R_{cj}/a \geq 1$ the width of the Landau bands $\Gamma_{Bj} = 2|V_{Bj}|$ reaches maximum if Eq. (2) holds true and is equal to zero if Eq. (3) is satisfied.

The density of states D_j under the conditions $V_0 \ll \varepsilon_{Fj}$, $N_j \gg 1$ and $1/\tau_{qj} \sim \omega_c$ is given by the following relationship [7]:

$$D_j / D_0 \approx 1 - 2J_0(2\pi V_{Bj} / \hbar\omega_c) \exp(-\pi / \omega_c \tau_{qj}) \cos(2\pi\varepsilon_{Fj} / \hbar\omega_c), \quad (6)$$

where $D_0 = m^*/\pi\hbar^2$. Using relations (1) and (6), the behavior of MISO in a two-subband ULSL can be described by formula [8]:

$$\Delta\rho_{\text{MISO}} / \rho_0 = A_{\text{MISO}} J_0(2\pi V_{B1} / \hbar\omega_c) J_0(2\pi V_{B2} / \hbar\omega_c) \exp(-2\pi / \omega_c \tau_q^{\text{MISO}}) \cos(2\pi\Delta_{12} / \hbar\omega_c). \quad (7)$$

In this formula, the role of $V(x)$ is taken into account by the factors $J_0(2\pi V_{Bj} / \hbar\omega_c)$, which are absent in Eq. (1).

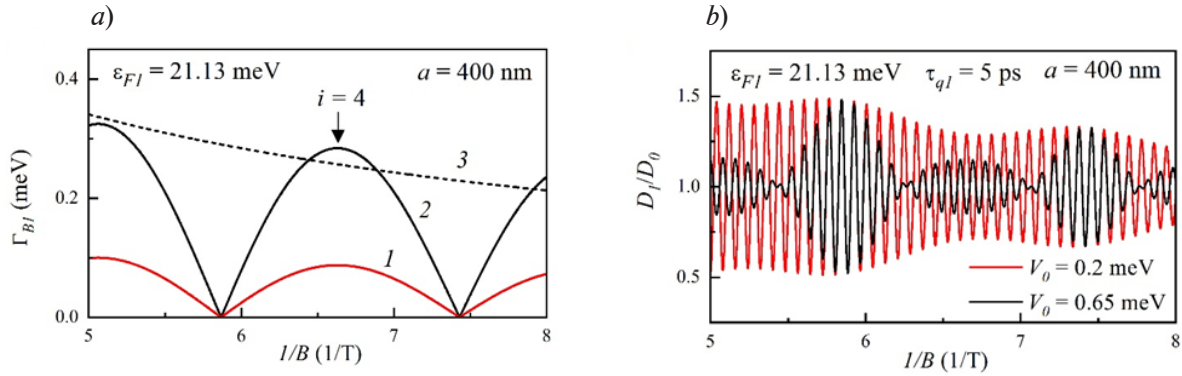


Fig. 1. Dependences $\Gamma_{B1}(1/B)$ calculated by Eq. (5) for two different values of V_0 : 0.2 (1), 0.65 meV (2), dependence $\hbar\omega_c(1/B)$ (3), the arrow indicates the maximum position for $i = 4$ (a); dependences of D_1/D_0 on $1/B$, calculated by Eq. (6) (b)

Figure 1, *a* shows the dependences $\Gamma_{B1}(1/B)$ for weak (1) and strong (2) modulation of the potential $V(x)$ with respect to $\hbar\omega_c$. In the strong modulation regime, there are intervals of $1/B$ where $\Gamma_{B1}(1/B) \sim \hbar\omega_c$. Fig. 1, *b* shows the dependences of D_1/D_0 on $1/B$, calculated by Eq. (6) for a fixed ε_{F1} and for two different values of V_0 . It can be seen that the dependences of D_1/D_0 on $1/B$ for weak and strong potential modulation are out of phase in the regions where $\Gamma_{B1}(1/B) \sim \hbar\omega_c$. This behavior is due to the role of Van Hove singularities in the spectrum of states at the edges of the Landau bands. Eqs. (6) and (7) predict a significant transformation of the MISO when $\Gamma_{B1}(1/B) \sim \hbar\omega_c$. The purpose of this work is to experimentally detect the MISO under such conditions.

Materials and Methods

The initial heterostructure was a single GaAs quantum well 26 nm wide with short-period AlAs/GaAs superlattice barriers [9, 10]. The charge carriers in the quantum well were provided by means of Si δ doping. Single Si δ -doped layers were located on both sides of a single GaAs quantum well at a distance of 29.4 nm from its boundaries. The heterostructure was grown by molecular beam epitaxy on a (100) GaAs substrate. The studies were carried out on double bridges 100 μm long and 50 μm wide. They were fabricated using optical photolithography and liquid etching. One bridge was the control one, and the ULSL was formed on the second one (see inset to Fig. 2, *a*).

The ULSL was a set of Ti/Au strips with a period $a = 400$ nm. The ULSL was fabricated using electron beam lithography. The experiments were carried out at $T = 4.2$ K in fields $B < 2$ T. The resistance of the samples ρ_{xx} and ρ_{xy} was measured at an alternating current not exceeding 1 μA with a frequency of ~ 1 kHz. In the control bridge, the electron concentration and mobility were: $n_H \approx 8.2 \times 10^{15} \text{ m}^{-2}$; $\mu \approx 115 \text{ m}^2/\text{Vs}$. The presence of superlattice slightly reduces n_H and μ . In the ULSLs under study, the modulating potential arises without applying voltage V_g to the metal strips. One of the reasons for such modulation is the elastic mechanical stresses that arise between the metal strips and the heterostructure [11].

Results and Discussion

The results of ρ_{xx}/ρ_0 versus B measurements in the control bridge and in the ULSL are shown in Fig. 2, *a*. The MISO with frequency $f_{12} \approx 8.8$ T are detected in the control bridge. The intersubband splitting determined from the frequency f_{12} is $\Delta_{12} \approx 15$ meV. In the ULSL the more pronounced are the oscillations whose maxima and minima positions are given by Eqs. (2) and (3), which allows us to consider them commensurate. The Fourier analysis of CO shows two frequencies ($f_{CO1} = 0.64$ T and $f_{CO2} = 0.36$ T) in good agreement with their expected values. Figure 2, *b* shows the dependences of ρ_{xx}/ρ_0 versus $1/B$ in the region of magnetic fields, where the MISO in the control bridge and the ULSL are in antiphase.

The dependences of $\Delta\rho_{\text{MISO}}/\rho_0$ versus $1/B$ for the control bridge and the ULSL, obtained after subtracting from the experimental curves the CO and monotonic components, are shown in Fig. 3, *a*. The amplitude of MISO in the ULSL is strongly suppressed compared to the control

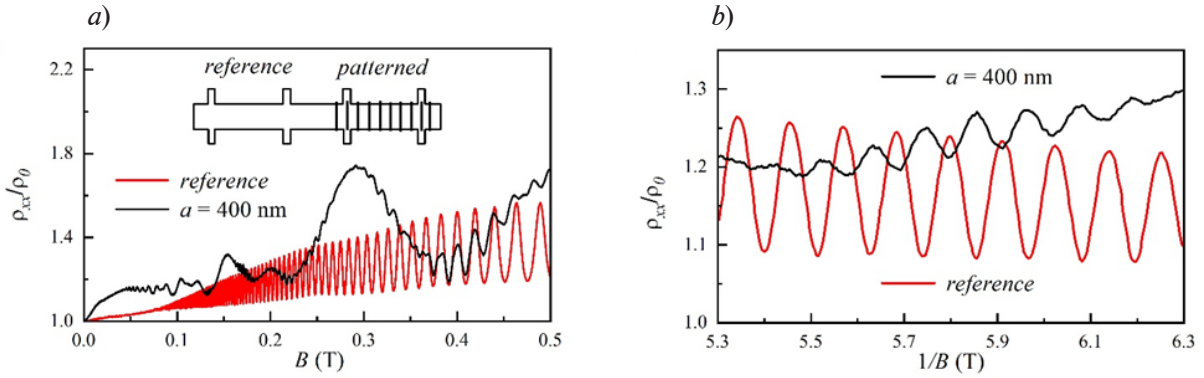


Fig. 2. Dependences of ρ_{xx}/ρ_0 versus B measured at $T = 4.2$ K in the control bridge and in the ULSL: the inset shows the schematics of the sample (a); dependences of ρ_{xx}/ρ_0 on $1/B$ in the region of the MISO phase flip (b)

bridge. The dependences of $\Delta\rho_{\text{MISO}}/\rho_0$ on $1/B$ for the control bridge and the ULSL calculated from Eq. (7) are shown in Fig. 3, b. Good agreement between the experimental dependences and those calculated is observed for $V_0 = 0$ and $\tau_q^{\text{MISO}} = 8$ ps for the control bridge, and for $V_0 = 0.65$ meV and $\tau_q^{\text{MISO}} = 6$ ps for the ULSL. A decrease in τ_q^{MISO} in the ULSL indicates that the deposition of a grating leads to an increase in the random scattering potential in the two-subband electron system under study.

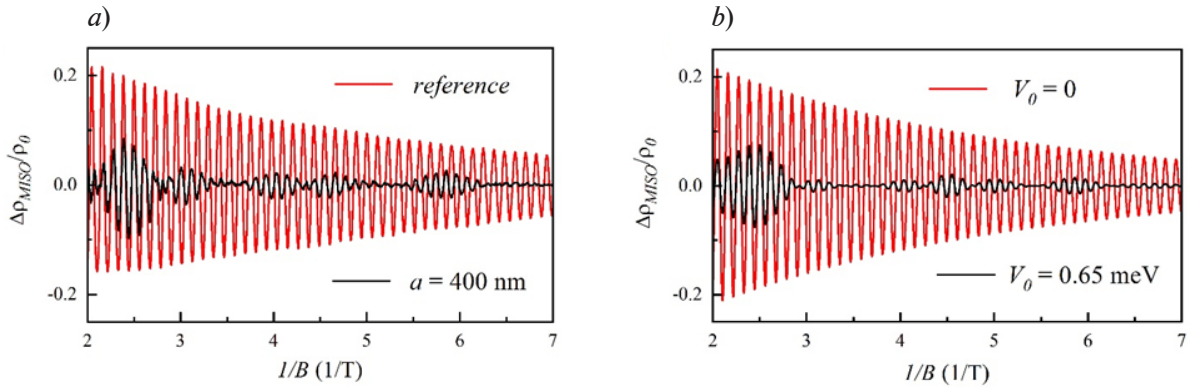


Fig. 3. Dependences of $\Delta\rho_{\text{MISO}}/\rho_0$ versus $1/B$ for the control bridge and the ULSL (a); dependences of $\Delta\rho_{\text{MISO}}/\rho_0$ versus $1/B$, calculated by Eq. (7): $n_1 = 6 \times 10^{15} \text{ m}^{-2}$, $n_2 = 1.9 \times 10^{15} \text{ m}^{-2}$, $A_{\text{MISO}} = 0.4$, for the control bridge $\tau_q^{\text{MISO}} = 8$ ps, for the ULSL $\tau_q^{\text{MISO}} = 6$ ps (b)

Fig. 4, a shows $\Delta\rho_{\text{MISO}}/\rho_0$ versus $1/B$ for the control bridge and the ULSL in two regions where they are in-phase and out-of-phase. The dependences of Γ_{Bj} on $1/B$ calculated for $V_0 = 0.65$ meV are shown in Figs. 4, b. Two regions are highlighted in gray in which MISO for the control bridge and the ULSL are in-phase and out-of-phase. In region 1: $\Gamma_{B1} < \hbar\omega_c/2$. In region 2: $\Gamma_{B1} < \hbar\omega_c/2$, and $\Gamma_{B2} \sim \hbar\omega_c$. In region 1, the oscillations of D_1/D_0 and D_2/D_0 versus $1/B$ for the control bridge and for the ULSL are in phase under condition that $1/\tau_{qj} \sim \omega_c$. In this case, $V(x)$ leads only to a decrease in the amplitude of MISO, but does not change their phase. In region 2, the oscillations D_1/D_0 and D_2/D_0 are out of phase. In this situation, $V(x)$ leads not only to a suppression of the MISO amplitude, but also to a change in their phase. Thus, the "reversal" of MISO is due to the fact that in region 2: $\Gamma_{B1} < \hbar\omega_c/2$, and $\Gamma_{B2} \sim \hbar\omega_c$.

The observed flip of the MISO is fundamentally different from the flip of the SdH oscillations in the ULSL [12]. The SdH oscillations in quasi-two-dimensional systems are due to the Landau levels induced modulation of the density of states D_j . When $\hbar\omega_c$ changes, the regions with a higher D_j cross E_F periodically in $1/B$, which leads to SdH oscillations. The one-dimensional potential leads to Van Hove singularities in the dependence of D_j on energy ε . The density of states at the edges of the Landau bands has a maximum, while in the center it has a minimum.

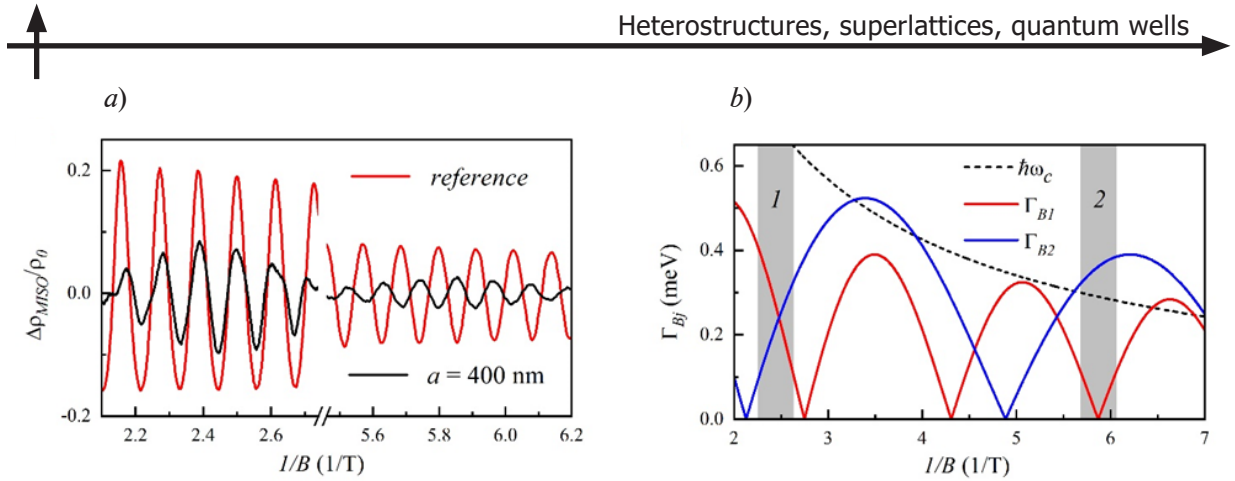


Fig. 4. Dependences of $\Delta\rho_{\text{MISO}}/\rho_0$ versus $1/B$ in two narrow intervals (a); dependences of Γ_{Bj} on $1/B$, calculated by Eq. (5): $n_1 = 6 \times 10^{15} \text{ m}^{-2}$, $n_2 = 1.9 \times 10^{15} \text{ m}^{-2}$, $a = 400 \text{ nm}$, $V_0 = 0.65 \text{ meV}$, shaded regions 1 and 2 denote intervals of $1/B$, in which the MISO for the control bridge and the ULSL are in-phase and out-of-phase (b)

Such a “splitting” in $D_j(\epsilon)$ leads, under the conditions $\Gamma_{Bj} \sim \hbar\omega_c$ and $1/\tau_{qj} \sim \hbar\omega_c$, to a flip of the SdH oscillations [12].

In a two-subband system, as $1/B$ changes, resonant transitions of electrons between the Landau levels of different subbands occur periodically giving rise to the MISO. The resonant nature of such transitions is not related to the position of E_F , which makes the physics behind the MISO fundamentally different from that of the SdH oscillations. The MISO maxima arise when the Landau levels of different subbands coincide. The one-dimensional periodic potential by changing $D_j(\epsilon)$ significantly transforms the conditions for resonant transitions. In this case, the conditions for resonant magneto-intersubband transitions arise only in certain intervals of B , which is observed experimentally.

Conclusion

To summarize, we fabricated an ULSL based on a highly mobile two-subband electron system; MISO were considered in this ULSL assuming overlapping Landau bands. We observed a “flip” of the MISO in some ranges of magnetic fields. We established that the “flip” of the MISO occurs when the width of the Landau bands in the first subband is significantly less than the cyclotron energy, while the width of the Landau bands in the second subband is comparable to the cyclotron energy.

REFERENCES

1. Polyanovskii V.M., Anomalous temperature-dependence of the amplitude of quantum oscillations of the magnetoresistance in quasitwo-dimensional systems, *Sov. Phys. Semicond.* 22 (1988) 1408.
2. Raichev O.E., Magnetic oscillations of resistivity and absorption of radiation in quantum wells with two populated subbands, *Phys. Rev. B* 78 (2008) 125304.
3. Bykov A.A., Nomokonov D.V., Goran A.V., Strygin I.S., Bakarov A.K., Abedi S., Vitkalov S.A., Suppression of magneto-intersubband resistance oscillations by large-scale fluctuations of the intersubband energy splitting, *JETP Lett.* 114 (2021) 423.
4. Weiss D., von Klitzing K., Ploog K., Weimann G., Magnetoresistance oscillations in a two-Dimensional electron gas induced by a submicrometer periodic potential, *Europhys. Lett.* 8 (1989) 179.
5. Beenakker C.W.J., Guiding-center-drift resonance in a periodically modulated two-dimensional electron gas, *Phys. Rev. Lett.* 62 (1989) 2020.
6. Winkler R.W., Kotthaus J.P., Ploog K., Landau band conductivity in a two-dimensional electron system modulated by an artificial one-dimensional superlattice potential, *Phys. Rev. Lett.* 62 (1989) 1177.
7. Endo A., Iye Y., Modulation of the Shubnikov–de Haas oscillation in unidirectional lateral superlattices, *J. Phys. Soc. Jpn.* 77 (2008) 054709.

8. **Bykov A.A., Strygin I.S., Goran A.V., Nomokonov D.V., Marchishin I. V., Bakarov A.K., Rodyakina E.E., Latyshev A.V.**, Modulation of magneto-intersubband oscillations in a one-dimensional lateral superlattice, JETP Lett. 110 (2019) 354.

9. **Friedland K.-J., Hey R., Kostial H., Klann R., Ploog K.**, New concept for the reduction of impurity scattering in remotely doped GaAs quantum wells, Phys. Rev. Lett. 77 (1996) 4616.

10. **Bykov A.A., Strygin I.S., Goran A.V., Nomokonov D.V., Bakarov A.K.**, Dependences of the transport scattering time and quantum lifetime on the two-dimensional electron gas density in modulation-doped single GaAs quantum wells with AlAs/GaAs short-period superlattice barriers, JETP Lett. 112 (2020) 437.

11. **Larkin I.A., Davies J.H., Long A.R., Cuscy R.**, Theory of potential modulation in lateral surface superlattices. II. Piezoelectric effect, Phys. Rev. B 56 (1997) 15242.

12. **Edmonds K.W., Gallagher B.L., Main P.C., Overend N., Wirtz R., Nogaret A., Henini M., Marrows C.H., Hickey B.J., Thoms S.**, Magnetoresistance oscillations due to internal Landau band structure of a two-dimensional electron system in a periodic magnetic field, Phys. Rev. B 64 (2001) 041303(R).

THE AUTHORS

STRYGIN Ivan S.

vanya-91@yandex.ru

ORCID: 0000-0002-0254-2925

BYKOV Aleksei A.

bykov@isp.nsc.ru

ORCID: 0000-0002-2776-1657

Received 07.12.2022. Approved after reviewing 08.12.2022. Accepted 06.02.2023.