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

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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

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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 \( \rho_{xx} \) 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]:

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

where \( \rho_0 = \rho_{xx}(B = 0) \), \( A_{\text{MISO}} = 2\tau_1 / \tau_{12} \), \( \tau_1 \) is the transport scattering time, \( \tau_{12} \) is the intersubband scattering time, \( \tau_q^{\text{MISO}} = 2\tau_1 \tau_{12} / (\tau_{11} + \tau_{12}) \), \( \omega_c \) is the quantum lifetime, \( \Delta_{12} \) 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:

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

\[
2R_{cj} / a = (i - 1/4),
\]

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 \( V_0 << E_F - E_j = \epsilon_{Fj} \) (\( E_F \) is the position of the Fermi level), the dependence of the Landau level \( E_{nj}(x_0) \) with \( N_j >> 1 \) on \( x_0 \) is given by the expression [6]:

\[
E_{nj}(x_0) \approx E_j + \left(N_j + 1/2\right)\hbar \omega_c + V_{bj} \cos\left(2\pi x_0 / a\right),
\]

\[
V_{bj} = V_0 J_0\left(2\pi R_{cj} / a\right).
\]

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 \( V_0 << \epsilon_{Fj}, N_j >> 1 \) and \( 1/\tau_{qj} \sim \omega_c \) is given by the following relationship [7]:

\[
D_j / D_0 \approx 1 - 2J_0\left(2\pi V_{bj} / \hbar \omega_c\right) \exp\left(-\pi / \omega_c \tau_{qj}\right) \cos\left(2\pi \epsilon_{Fj} / \hbar \omega_c\right),
\]

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]:

\[
\Delta \rho_{\text{MISO}} / \rho_0 = A_{\text{MISO}} J_0\left(2\pi V_{ja} / \hbar \omega_c\right) J_0\left(2\pi V_{sa} / \hbar \omega_c\right) \exp\left(-2\pi / \omega_c \tau_q^{\text{MISO}}\right) \cos\left(2\pi \Delta_{12} / \hbar \omega_c\right).
\]
Figure 1, a shows the dependences $\Gamma_{a1}(1/B)$ 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 $\Gamma_{a1}(1/B) \sim \hbar\omega_c$. Fig. 1, b shows the dependences of $D_1/D_0$ on $1/B$, calculated by Eq. (6) for a fixed $\varepsilon_F$ 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 $\Gamma_{a1}(1/B) \sim \hbar\omega_c$. 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 $\Gamma_{a1}(1/B) \sim \hbar\omega_c$. 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 $\delta$-doping. Single Si $\delta$-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 $\rho_x$ and $\rho_y$ was measured at an alternating current not exceeding 1 μA with a frequency of $\sim 1$ kHz. In the control bridge, the electron concentration and mobility were: $n_e \approx 8.2 \times 10^{15}$ m$^{-2}$; $\mu \approx 115$ m$^2$/Vs. The presence of superlattice slightly reduces $n_e$ and $\mu$. 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 $\rho_x/\rho_0$ 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 $\Delta \omega \approx 15$ 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 ($f_{\text{CO1}} = 0.64$ T and $f_{\text{CO2}} = 0.36$ T) in good agreement with their expected values. Figure 2, b shows the dependences of $\rho_x/\rho_0$ 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 bridge.
Fig. 2. Dependences of $\rho_{xx}/\rho_0$ 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 $\rho_{xx}/\rho_0$ on $1/B$ in the region of the MISO phase flip (b).

Bridge. The dependences of $\Delta \rho_{MISO}/\rho_0$ 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 $\tau_{MISO}^{q} = 8$ ps for the control bridge, and for $V_0 = 0.65$ meV and $\tau_{MISO}^{q} = 6$ ps for the ULSL. A decrease in $\tau_{MISO}^{q}$ 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 $\Delta \rho_{MISO}/\rho_0$ versus $1/B$ for the control bridge and the ULSL (a); dependences of $\Delta \rho_{MISO}/\rho_0$ versus $1/B$, calculated by Eq. (7): $n_1 = 6 \times 10^{11}$ m$^{-2}$, $n_2 = 1.9 \times 10^{15}$ m$^{-2}$, $A_{MISO} = 0.4$, for the control bridge $\tau_{MISO}^{q} = 8$ ps, for the ULSL $\tau_{MISO}^{q} = 6$ ps (b).

Fig. 4, a shows $\Delta \rho_{MISO}/\rho_0$ 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 $\Gamma_B^{q}$ 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: $\Gamma_B^{q} < \hbar \omega_c / 2$. In region 2: $\Gamma_B^{q} < \hbar \omega_c / 2$, and $\Gamma_B^{q} \sim \hbar \omega_c$. 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 $1/\tau_{MISO}^{q} \sim \omega_c$. 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: $\Gamma_B^{q} < \hbar \omega_c / 2$, and $\Gamma_B^{q} \sim \hbar \omega_c$.

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 $D$. When $\hbar \omega_c$ changes, the regions with a higher $D$ 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 $D$ on energy $\varepsilon$. The density of states at the edges of the Landau bands has a maximum, while in the center it has a minimum.
Heterostructures, superlattices, quantum wells

Fig. 4. Dependences of $\Delta \rho_{\text{MISO}}/\rho_0$ versus $1/B$ in two narrow intervals (a); dependences of $\Gamma_{Bj}$ on $1/B$, calculated by Eq. (5): $n_1 = 6 \times 10^{13}$ m$^{-2}$, $n_2 = 1.9 \times 10^{15}$ m$^{-2}$, $a = 400$ nm, $V_0 = 0.65$ 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 $D_j(\varepsilon)$ leads, under the conditions $\Gamma_{Bj} \sim \hbar \omega_c$ and $1/\tau_{ij} \sim \hbar \omega_c$, 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 $D_j(\varepsilon)$ 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**


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Received 07.12.2022. Approved after reviewing 08.12.2022. Accepted 06.02.2023.