Letter

Microwave-induced zero-resistance states in a high-mobility two-subband electron system

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Abstract
In this study, a selectively-doped GaAs/AlAs heterostructure was used to fabricate a high-mobility two-subband electronic system with a substantially different concentration of electrons in the subbands. We observe microwave photoresistance at high numbers of magneto-intersubband oscillations (MISO). The system under study demonstrates microwave-induced resistance oscillations (MIRO) and MISO interference. The MIRO in the studied two-subband system appears in lower magnetic fields compared to the MISO. This is an indication of some additional mechanism that exists in the two-subband system and is responsible for the MISO amplitude damping in low magnetic fields, while it does not affect the MIRO amplitude. Zero resistance states appear in the system under study under microwave irradiation in a narrow range of magnetic fields near the MISO maxima.

Keywords: microwave photoresistance, MIRO, MISO

The discovery of microwave-induced resistance oscillations (MIRO) in high-mobility two-dimensional (2D) electron systems at high filling factors [1, 2] and zero resistance states (ZRS) [3, 4] appearing in the MIRO minima inspired intensive theoretical and experimental research of these phenomena [5]. The search for new electron systems where these phenomena manifest themselves continues [6–10], as well as development of new theoretical models for their interpretation [11].

MIRO are periodic in the inverse magnetic field, similar to Shubnikov–de-Haas (SdH) oscillations. Their period is controlled by $\omega/\omega_c$ ratio and their minima are placed at $\omega/\omega_c = j + \frac{1}{4}$, where $\omega = 2\pi f$ is the microwave radiation frequency, $\omega_c = eB/m^*$ is the cyclotron frequency of electrons with effective mass $m^*$ in magnetic field $B$, and $j$ is an integer. The resistance of a 2D electron system exposed to microwave irradiation can be written as $\rho_\omega = \rho_{xx} + \rho_{\text{MIRO}}$, where $\rho_{xx}$ is the resistance in the absence of irradiation and $\rho_{\text{MIRO}}(\omega/\omega_c)$ is sign-alternating photoresistance.

There are two commonly used models that explain MIRO based on elastic and inelastic scattering of non-equilibrium electrons [12–15]. Both models propose the same expression for MIRO amplitude in the case of overlapping Landau levels [5]:

$$\rho_{\text{MIRO}} \propto -(\omega/\omega_c)P_\omega\lambda^2\sin(2\pi\omega/\omega_c),$$

(1)

where $P_\omega$ is a dimensionless parameter proportional to microwave power, $\lambda = \exp(-\pi/\omega_c\tau_q)$ is the Dingle factor and $\tau_q$ is the quantum relaxation lifetime. According to (1), with $P_\omega$ increasing $\rho_{\omega}$ should turn negative in the MIRO minima. However the experiment shows $\rho_{\omega} \approx 0$ in the MIRO minima [3, 4, 14, 16, 17]. It is commonly assumed that ZRS are the result of instability of absolute negative resistance which...
leads to the formation of current domains [18–20]. There are also alternative explanations of ZRS (see [21–24] for more references).

Unlike single-subband electron systems, high-mobility two-subband electron systems in addition to SdH oscillations exhibit MISO in perpendicular magnetic field and at low temperatures [25–27]. These quantum oscillations exist because of intersubband scattering and their period in the inverse magnetic field is \( \Delta_{12}/\hbar \omega_c \), where \( \Delta_{12} \) is the energy gap between the subbands. The MISO amplitude in a two-subband system is [26, 27]:

\[
\rho_{\text{MISO}} \propto \lambda_1 \lambda_2 \cos(2\pi \Delta_{12}/\hbar \omega_c),
\]

where \( \lambda_1 = \exp(-\pi/\omega_c \tau_{q1}) \), \( \lambda_2 = \exp(-\pi/\omega_c \tau_{q2}) \) and \( \tau_{q1}, \tau_{q2} \) are the quantum electron lifetimes in subbands.

Conducted research has shown that the microwave photoresistance in a two-subband electron system exhibits MISO superimposed on MIRO [28]. The MISO amplitude increases in the areas where \( \rho_{\text{MISO}} \) is positive, while in the areas of negative \( \rho_{\text{MISO}} \), the MISO becomes inverted. This behavior was explained by the MIRO and MISO interference [29]. In two-subband systems, ZRS have been so far observed only in a 45 nm wide quantum well with approximately equal population of the subbands [30] where the condition \( 2\hbar \omega \sim \Delta_{12} \) was met. In this paper, we observe ZRS under the condition \( \hbar \omega \ll \Delta_{12} \), which allows for a far more detailed investigation of this non-equilibrium phenomenon in two-subband systems.

The selectively doped heterostructure under study was a single 30 nm wide GaAs quantum well with AlAs/GaAs superlattice barriers on both sides [31, 32]. Superlattice barriers were in the form of 15 alternating 1.41 nm wide AlAs and 2.83 nm wide GaAs layers. Charge carriers in the quantum well were provided by Si \( \delta \)-doping. Single Si \( \delta \)-doped layers were placed on both sides of the quantum well inside the GaAs layers of the superlattice barriers at the distance of 32.5 nm from the quantum well interfaces. The heterostructure was grown using molecular-beam epitaxy on (100) GaAs substrate.

The measurements were carried out at the temperature \( T = 1.6 \text{ K} \) in the magnetic fields \( B < 0.5 \text{ T} \). Hall bars with the width \( W = 50 \text{ \mu m} \) and the length \( L = 450 \text{ \mu m} \) were fabricated using optical photolithography and wet etching. The resistance of 2D electron gas was measured using alternating current using optical photolithography and wet etching. The Hall concentration \( n_H \) is a bit higher than the sum \( n_1 + n_2 \approx 6.75 \times 10^{15} \text{ m}^{-2} \) which may be attributed to the X electrons in the system studied [31, 32]. The difference \( f_{\text{SdH2}} - f_{\text{SdH1}} \approx 5.78 \text{ T} \) matches the MISO frequency, which confirms our interpretation of the spectrum. Calculated from the MISO frequency, \( \Delta_{12} \approx 9.83 \text{ meV} \) is in a good agreement with the self-consistent calculation of the band structure of our quantum well.

Figure 2(a) shows the dependence \( \rho_{\text{xx}}(B)/\rho_0 \) in the presence of microwave irradiation. It is quite clear that the microwave field substantially alters the magnetoresistance of the high-mobility two-subband electron system. The Fourier analysis of \( \rho_{\text{xx}}(1/B)/\rho_0 \) is presented in figure 2(b). It reveals four frequencies: \( f_{\text{MISO}}, f_{\text{MISO}} - f_{\text{MIRO}}, f_{\text{MISO}} - 2f_{\text{MIRO}} \) with the highest peak corresponding to the MIRO. The period of these oscillations, similarly to single-subband systems [1, 2] is determined by \( \omega_c \). Unlike single-subband systems, however, the spectrum contains three more frequencies: \( f_{\text{MISO}} - f_{\text{MIRO}}, f_{\text{MISO}} + f_{\text{MIRO}} \), which can be attributed to the MIRO and MISO interference that was earlier discovered in two-subband systems with little difference in the electron population of the subbands [28, 29]. However, in the studied system, the interference is clearly visible even without frequency analysis due to the large difference between \( f_{\text{MIRO}} \) and \( f_{\text{MISO}} \).

Microwave power dependence of the combination of MIRO and MISO has not yet been systematically studied in our system. Similarly to the previously studied two-subband systems [33], microwave photoresistance first increases with rising power, then it decreases. The results presented in the paper
are for the range of power where photoresistance increases with rising power. We do not have an accurate temperature dependence of microwave photoresistance in the studied systems. ZRS are not present at \( T = 4.2 \) K, while MIRO appear in lower magnetic fields comparing to MISO, similarly to the case of \( T = 1.6 \) K (see figure 3(a)). As can be seen, the MIRO manifest themselves at \( B > 0.02 \) T while the MISO appear only at \( B > 0.04 \) T.

The dependence of \( \rho_{\text{MIRO}}(1/B) \omega / \rho_{\text{0}} \omega \) is linear in a semilogarithmic scale (see figure 3(b)) which is in qualitative agreement with (1). The quantitative dependence of \( \rho_{\text{MIRO}}(1/B) \omega / \rho_{\text{0}} \omega \) is:

\[
\rho_{\text{MIRO}} \omega / \rho_{\text{0}} \omega = A_{\text{MIRO}} \exp(-2\pi / \omega \tau_{\text{MIRO}}),
\]

where \( A_{\text{MIRO}} = 0.16 \) and \( \tau_{\text{MIRO}} = 15 \) ps. MIRO amplitude in a two-subband system is \([33]\): \( \rho_{\text{MIRO}} \omega / \rho_{\text{0}} \omega = A_{\text{MIRO}} \lambda_{1}^{2} + A_{\text{MIRO}} \lambda_{2}^{2} \), where \( A_{\text{MIRO}} \) and \( A_{\text{MIRO}} \) are fitting parameters depending on microwave power, inelastic scattering time, transport scattering times, and electron concentration in subbands. Equation (3) holds true when at least one of the following conditions are satisfied: \( \lambda_{1} = \lambda_{2} \); \( A_{\text{MIRO}} \lambda_{1}^{2} \gg A_{\text{MIRO}} \lambda_{2}^{2} \) or \( A_{\text{MIRO}} \lambda_{1}^{2} \ll A_{\text{MIRO}} \lambda_{2}^{2} \), which means that either \( \tau_{\text{q1}} \approx \tau_{\text{q2}} \) or MIRO amplitude is determined by one of subbands in our system.

The experimental curve \( \rho_{\text{MISO}}(1/B) \rho_{\text{0}} / \rho_{\text{0}} \) is not linear in semilogarithmic scale (figure 3(b)) and does not match (2). Such behavior of the MISO amplitude was earlier observed in a two-subband system with a lower mobility \([34]\). It has been recently suggested that nonparabolic nature of electronic spectrum can be one of the possible reasons of MISO amplitude damping at low magnetic fields \([35]\). Large-scale fluctuation of the energy gap \( \Delta_{12} \) caused by technological fluctuations of GaAs quantum well width could be another possible reason. We are not aware of any theoretical works that explain MISO amplitude damping in low magnetic fields. The comparison of the experimental curves \( \rho_{\text{MIRO}}(1/B) \omega / \rho_{\text{0}} \omega \) and \( \rho_{\text{MISO}}(1/B) \rho_{\text{0}} / \rho_{\text{0}} \) leads us to the conclusion that the additional mechanism responsible for MIRO damping in low magnetic fields does not affect, or has a very limited influence on the MIRO amplitude.

In order to mathematically describe MISO amplitude damping in low magnetic fields we introduce one more factor in addition to the Dingle factor, similar to how it is done for SdH oscillations amplitude in non-homogeneous 2D electron gas \([36]\):

\[
\rho_{\text{MISO}} / \rho_{0} = A_{\text{MISO}} \exp(-2\pi / \omega \tau_{\text{qMISO}}) \exp(-2\pi / \omega \tau_{\text{qDAMP}})^{b},
\]

where \( A_{\text{MISO}} \) is a dimensionless parameter, \( 2\pi \tau_{\text{MISO}} = 1/r_{\text{qMISO}} + 1/r_{\text{qDAMP}} \), \( \tau_{\text{qDAMP}} \) is quantum time that takes into account MISO damping at low magnetic fields, \( b \) is the power exponent. This equation quantitatively describes \( \rho_{\text{MISO}} / \rho_{0} \) in the whole experimental range of magnetic fields with the following fitting parameters: \( A_{\text{MISO}} = 0.4 \), \( \tau_{\text{qMISO}} = 22 \) ps, \( \tau_{\text{qDAMP}} = 46 \) ps, \( b = 6 \). The theoretic model suggested in \([36]\) describes Shubnikov–de Haas oscillation damping in a single-subband system with large-scale fluctuations of electron
conclusion that $\tau \ll \nu$ be the case in our system because in that case the three conditions are satisfied. The first one ($\tau \ll \nu$) implies that the electron quantum lifetime in the subbands $\approx 15$ ps in the studied system. In the two-subband system with $n_1 \approx n_2$ and $\tau_{q_1} \approx \tau_{q_2}$ states with $\rho_\omega \approx 0$ have been observed for $\tau_\omega \approx 7.1$ ps [30]. The high quality of the two-subband system under study is testified by the dependence shown in figure 4(a). It is clearly seen that the MIRO gets inverted around the first MIRO minimum ($\omega/\omega_c = 1 + 1/4$) and the oscillations maxima numbered $k = 18$ and $20$ get transformed to the states with $\rho_\omega \approx 0$. However, the state with $\rho_\omega \approx 0$ does not appear around the second MIRO minimum (figure 4(b)). We expect that with increasing frequency up to 300 GHz ZRS will appear in our system not only at $\omega/\omega_c = 1.25$ but also at 2.25. We expect quenching of two-subband photoresistance under terahertz frequencies, same as in single-subband systems [41]. Our results show that ZRS are not present in MIRO minima. We presume that ZRS could appear in MIRO minima in more advanced multi-subband systems.

In conclusion, in this paper we have studied magnetotransport properties of a high-mobility two-subband electron system ($\mu > 300$ m$^2$/Vs$^{-1}$ at $T = 1.6$ K) fabricated using selectively doped 30 nm wide GaAs quantum well surrounded by AlAs/GaAs superlattice barriers on the sides. It was shown that both MIRO and ZRS appear in such a system under microwave irradiation. The ZRS appear only at the MIRO minima in a narrow magnetic field range near the MIRO maxima, which is attributed to the MIRO and MISO interference. Some additional mechanism is found to be responsible for the MIRO damping in low magnetic fields ($B < 0.1$ T) and not to be affecting the MIRO amplitude at the same time. The analysis of the MIRO amplitude dependence on $1/B$ at $B < 0.05$ T shows that the electron quantum lifetime in the subbands exceeds 15 ps at $T = 1.6$ K in our samples. We believe that the two-subband systems with high electron quantum lifetime can be found useful for the narrow-band reception of the microwave radiation.

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