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CONDENSED MATTER

# Zener Tunneling between the Landau Levels in a Two-Dimensional Electron System with One-Dimensional Periodic Modulation

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Nonlinear magnetotransport in a two-dimensional electron gas in one-dimensional lateral lattices fabricated from a selectively doped GaAs/AlAs heterostructure is investigated. One-dimensional potential modulation is imposed on the two-dimensional electron gas by means of a set of metal strips formed on the planar surface of Hall bars. The dependences of the differential resistance $r_{xx}$ on the magnetic field $B < 0.5$ T are studied at a temperature $T = 1.6$ K in lattices with a period of $a \approx 200$ nm. It is shown that periodic oscillations in $r_{xx}(1/B)$ occur in such lattices under the action of a current-induced Hall field due to Zener tunneling between Landau levels. Interference is found between Zener oscillations and commensurability oscillations of $r_{xx}$ in two-dimensional electron systems with one-dimensional periodic modulation. The experimental results are qualitatively explained by the role of Landau bands in nonlinear transport at large filling factors.

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The quantization of the orbital motion of electrons in a magnetic field $B$ leads to a qualitative change in their energy spectrum. In particular, in an ideal two-dimensional (2D) system, the energy spectrum of electrons in a perpendicular magnetic field becomes discrete: $E_n = (n + 1/2)\hbar\omega_c$, where $n$ is the Landau level number, $\omega_c$ is the cyclotron frequency, and $m^*$ is the effective mass. A random scattering potential in a disordered electron system leads to the broadening of Landau levels: $\Gamma_n = \hbar/2\tau_q$, where $\Gamma_n$ is the width of the $n$th Landau level and $\tau_q$ is the quantum lifetime. In high-mobility 2D electron systems based on remotely doped GaAs quantum wells, the transport electron scattering time is $\tau_{tr} \gg \tau_q$. For this reason, there exists a range of strong magnetic fields in which Landau levels overlap ($\Gamma_n > \hbar\omega_c$).

The modulation of the energy spectrum of 2D electron states in strong magnetic fields in the case of a large number of filled Landau levels is the origin of a number of new nonequilibrium phenomena discovered over the past two decades in high-mobility 2D systems [1]. One of these phenomena is Zener tunneling between Landau levels [2–13]. It was shown that oscillations of the differential resistance $r_{xx}(1/B)$ appear in Hall bars with the width $W$ under the action of a direct electric current $I_{dc}$, the positions of the resistance maxima being determined by

$$2R_c eE_{dc} = j\hbar\omega_c, \quad (1)$$

where $R_c$ is the cyclotron radius, $E_{dc} = \rho_{xy}I_{dc}/W$ is the Hall electric field, $\rho_{xy}$ is the Hall resistivity, and $j$ is a positive integer. Zener tunneling between Landau levels results from backscattering of electrons by impurities, whereby the center of the cyclotron orbit of a scattered electron shifts by $2R_c$ and its energy changes by $j\hbar\omega_c$.

Here, we experimentally investigate Zener tunneling between Landau levels in a high-mobility 2D electron gas with one-dimensional periodic lateral potential modulation $V(x) = V_0\cos(2\pi x/a)$, where $a$ is the period of modulation. The probability of tunneling between Landau levels depends on their width $\Gamma_n$ and the backscattering time $\tau_\pi$ [14]. One-dimensional potential modulation slightly affects $\tau_\pi$ but significantly modifies the energy spectrum of 2D electrons in the magnetic field owing to the removal of degeneracy with respect to the coordinate $x_0$ of the center of the wavefunction, which leads to the appearance of Landau bands. The main goal of this work is to establish the role of Landau bands in Zener tunneling at large filling factors $\nu = 2E_F/\hbar\omega_c \gg 1$, where $E_F$ is the Fermi energy.

The magnetotransport properties of the 2D electron gas in a one-dimensional periodic potential have been studied for more than a quarter of a century [15–17]. The most striking effect found in such a system is the commensurability oscillations of the magnetoresistance [15]. In much the same way as Shubnikov–de Haas (SdH) oscillations, commensurability oscillations are periodic in $1/B$. The minima of commensurability oscillations occur under the condition

$$2R_c/a = (i - 1/4), \qquad (2)$$

where $i$ is a positive integer. These oscillations can be observed if the period $a$ is smaller than the electron mean free path $l_p = v_F\tau_{tr}$, where $v_F$ is the electron Fermi velocity. In the classical description, commensurability oscillations occur because of a resonance between the periodic motion of electrons along cyclotron orbits and the oscillatory drift of the orbit guiding center, induced by the potential $V(x)$ [18].

In the quantum description, a one-dimensional potential modulation results in the appearance of Landau bands. Under the condition $V_0/E_F \ll 1$, the energy of the Landau level with an index $n \gg 1$ is expressed as a function of $x_0$ as follows [17]:

$$E_n(x_0) \approx (n + 1/2)\hbar\omega_c + V_B\cos(2\pi x_0/a), \qquad (3)$$

$$V_B = V_0(a/\pi^2 R_c)^{1/2}\cos(2\pi R_c/a - \pi/4). \qquad (4)$$

According to Eqs. (3) and (4), the width of the Landau bands $\Gamma_B = 2|V_B|$ depends periodically on $1/B$. The dependence of $\Gamma_B$ and, thus, of the band conductivity on $1/B$ explains commensurability oscillations in the quantum description. The gap between the classical and quantum approaches to magnetotransport in weakly modulated 2D electron systems was eliminated very recently [19].

Here, we study nonlinear electron transport in one-dimensional lateral lattices made of a GaAs/AlAs heterostructure. The original selectively doped heterostructure was a GaAs quantum well confined between AlAs/GaAs superlattice barriers [20, 21]. The width of the quantum well was 13 nm. The heterostructure was grown by molecular beam epitaxy on a GaAs (100) substrate. The measurements were carried out at a temperature of $T = 1.6$ K in magnetic fields of $B < 0.5$ T on Hall bars with a width of $W = 50$ μm and a length of $L = 100$ μm. The bars were fabricated using optical lithography and wet etching. The electron density and mobility in the original heterostructure after illumination by a red LED at $T = 1.6$ K were $n_e \approx 8.3 \times 10^{15}$ m$^{-2}$ and $\mu \approx 235$ m$^2$/(V s), respectively.

The layout of the sample is shown schematically in the inset of Fig. 1a. The sample is a Hall bar with a metal lattice deposited on its planar surface. The lattices were made by means of electron-beam lithography and "lift-off" of a Au/Ti bilayer metal film. The thicknesses of the Au and Ti layers were 40 and 5 nm, respectively. The lattice represented a series of 100-nm-wide Au/Ti strips. The lattice period $a$ was 200 nm. The electron density and mobility in bars with a lattice after illumination by a red LED at $T = 1.6$ K were $n_e \approx 8.2 \times 10^{15}$ m$^{-2}$ and $\mu \approx 215$ m$^2$/(V s), respectively. The differential resistance $r_{xx} \approx V_{ac}/I_{ac}$ was measured at an alternating current $I_{ac} < 1$ μA with a frequency from 10 Hz to 1 kHz. Simultaneously with the alternating current, a direct current $I_{dc}$ from 0 to 100 μA was passed through the sample. For $I_{dc} = 0$, $r_{xx} = R_{xx}$.

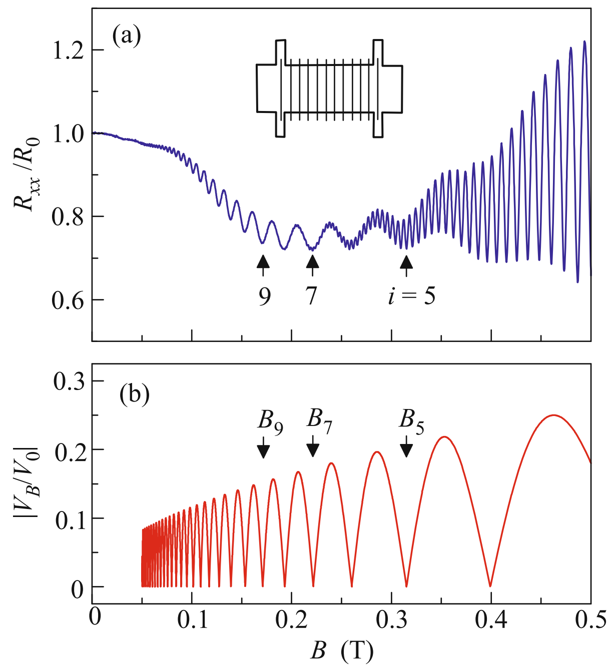


**Fig. 1.** (Color online) (a) Experimental magnetic field dependence of $R_{xx}/R_0$ measured for a Hall bar with a lattice at $T = 1.6$ K. The arrows indicate the minima of commensurability oscillations for $i = 5$, 7, and 9. The inset shows the simplified layout of the sample. (b) Theoretical dependence calculated by Eq. (4) with the parameters $a = 200$ nm and $n_e = 8.2 \times 10^{15}$ m$^{-2}$. The arrows indicate the magnetic fields $B_i$ for $i = 5$, 7, and 9.

The electron density $n_e$ in the selectively doped GaAs/AlAs heterostructure used for the fabrication of the lattices increased by ~0.2 × 10$^{15}$ m$^{-2}$ after illumination with a red LED at $T = 1.6$ K. The lateral periodic modulation of the potential $V(x)$ in the resulting lattices occurs because the increase in the electron density upon illumination is smaller beneath the metal strips than in the open areas of the sample [22]. If we assume that $n_e$ after illumination remains completely unchanged beneath the strips and increases only in the open areas of the bar, then the modulation amplitude in the lattices under study is $V_0 \approx 0.35$ meV.

Figure 1a shows the dependence $R_{xx}(B)/R_0$ (where $R_0$ is the resistance in zero magnetic field) in which two types of oscillations are observed. Both of them are periodic in the inverse magnetic field. Oscillations with a shorter period are SdH oscillations, and their period is determined by the ratio $E_F/\hbar\omega_c$. Oscillations with a larger period are commensurability oscillations, since the positions of their minima are determined by Eq. (2). This gives evidence of one-dimensional periodic modulation of the 2D electron gas in the studied lattices. The dependence of $|V_B/V_0|$ on $B$, shown in Fig. 1b, demonstrates that the width $\Gamma_B$ of the Landau bands is zero at the minima of commensurability oscillations ($B = B_i$) and attains maximum values at the oscillation maxima.

Figure 2a shows schematically the layout for measuring the differential resistance $r_{xx}$ and shows the dependences of $r_{xx}/R_0$ on $1/B$ for $I_{dc}$ = (line *1*) 0 and (line *2*) 80 μA. The maxima marked by arrows on line *2* originate from Zener tunneling, because their positions are described by Eq. (1). It can be seen that Zener oscillations, induced by the Hall electric field, interfere with commensurability oscillations. The behavior of commensurability oscillations is shown in more detail in Fig. 2b. The dependences of $\Delta r_{CO}/R_0$ on $1/B$ were obtained by subtracting the SdH oscillations and the nonoscillating components from experimental curves *1* and *2*. These dependences show that, in the presence of direct current, the phase of commensurability oscillations periodically changes by π. The three nodes where the phase change takes place are marked by arrows in Fig. 2b.

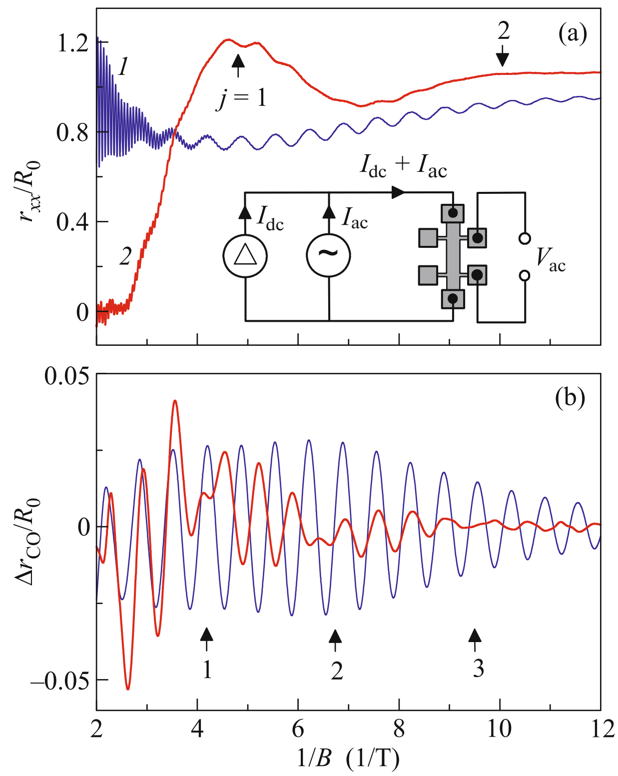


**Fig. 2.** (Color online) (a) Ratio $r_{xx}/R_0$ versus $1/B$ measured on a Hall bar with a latteral lattice at $T = 1.6$ K for $I_{dc}$ = (*1*) 0 and (*2*) 80 μA. The inset shows the layout for measuring the differential resistance $r_{xx} = V_{ac}/I_{ac}$. The arrows indicate the maxima of Zener oscillations for $j = 1$ and 2. (b) Ratio $\Delta r_{CO}/R_0$ versus $1/B$. The arrows indicate the nodes of the beats in commensurability oscillations.

The interference of commensurability oscillations and microwave photoresistance oscillations in a 2D electron system with one-dimensional periodic modulation was recently observed in [22], and, in addition, it was found that microwave-induced states with zero resistance $R_\omega \approx 0$ occur only at the minima of commensurability oscillations [23]. Furthermore, it was shown that, in the nonlinear regime, states with $r_{xx} \approx 0$ occur in one-dimensional lattices also only at the minima of commensurability oscillations [24]. These experimental results indicate the role of Landau bands in nonequilibrium phenomena arising in 2D electron systems with one-dimensional periodic modulation under the influence of microwave radiation or a static electric field.

The impact of Landau bands on SdH oscillations in the linear regime was studied in [25]. It was shown that modulation of SdH oscillations occurs in one-dimensional lateral superlattices based on a 2D electron gas in selectively doped heterostructures. The behavior of SdH oscillations for the case of strongly overlapping Landau levels and weak one-dimensional modulation of the 2D electron gas is described by the expression [25]

$$\Delta R_{SdH}/R_0 \approx 2A_{SdH}X(T)\Delta D/D_0, \quad (5)$$

where $X(T) = (2\pi^2 k_B T/\hbar\omega_c)/\sinh(2\pi^2 k_B T/\hbar\omega_c)$, $\Delta D/D_0 = -2J_0(2\pi V_B/\hbar\omega_c)\delta\cos(2\pi E_F/\hbar\omega_c)$, $\delta = \exp(-\pi/\omega_c\tau_q)$ is the Dingle factor, and $A_{SdH}$ is a dimensionless parameter on the order of unity.

In comparison to an unmodulated 2D electron gas, $\Delta D/D_0$ in latteral lattices acquires an additional factor $J_0(2\pi V_B/\hbar\omega_c)$, which is responsible for the modulation of the amplitude of SdH oscillations. At the minima of commensurability oscillations ($V_B = 0$), the additional factor is $J_0(2\pi V_B/\hbar\omega_c) = 1$ and is independent of $B$. At the maxima of commensurability oscillations, this factor is smaller than unity, decreases with increasing $1/B$, and vanishes under the condition $|V_B| = 0.3827\hbar\omega_c$ [25]. Formula (5) is valid only for $|V_B| < 0.3827\hbar\omega_c$ [25]. In this case, the periodic potential causes only an additional broadening of the Landau levels.

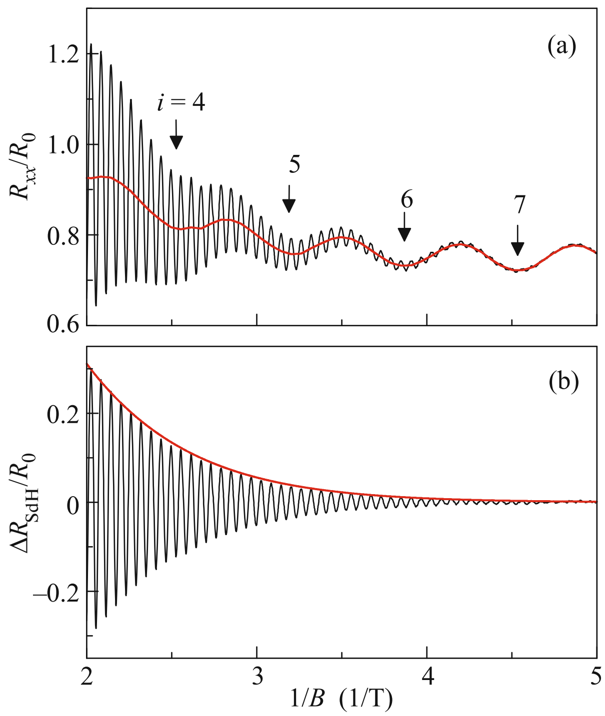


**Fig. 3.** (Color online) (a) (Thin line) Measured ratio $R_{xx}/R_0$ versus $1/B$ and (thick line) the smoothed dependence. The arrows indicate the minima of commensurability oscillations for $i = 4$, 5, 6, and 7. (b) (Thin line) Ratio $\Delta R_{SdH}/R_0$ versus $1/B$ and (thick line) the ratio calculated by Eq. (5) with the parameters $A_{SdH} = 0.85$, $V_0 = 0$, $\tau_q = 2.3$ ps, and $\cos(2\pi E_F/\hbar\omega_c) = -1$.

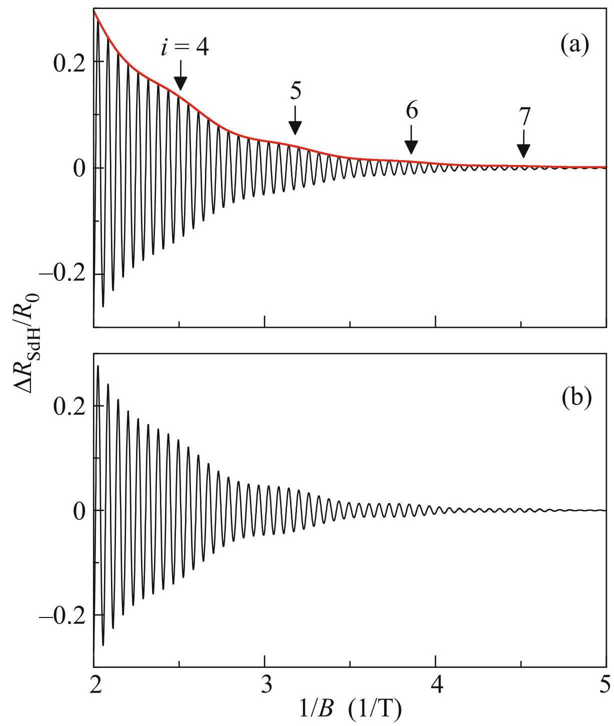


**Fig. 4.** (Color online) (a) Ratio $\Delta R_{SdH}/R_0$ versus $1/B$ calculated by Eq. (5) with the parameters $A_{SdH} = 0.85$, $V_0 = 0.35$ meV, and $\tau_q = 2.3$ ps (thin line) without and (thick line) with the condition $\cos(2\pi E_F/\hbar\omega_c) = -1$. The arrows indicate the minima of commensurability oscillations for $i = 4$, 5, 6, and 7. (b) Ratio $\Delta R_{SdH}/R_0$ versus $1/B$ calculated by Eq. (5) with the parameter $\Delta D/D_0 = -2\exp(-\pi/\omega_c\tau_q^*)\cos(2\pi E_F/\hbar\omega_c)$, $\tau_q^* = \tau_q^0 J_0(2\pi V_B/\hbar\omega_c)$, $A_{SdH} = 0.85$, $V_0 = 0.35$ meV, and $\tau_q = 2.3$ ps.

Figure 3a shows the experimental dependence of $R_{xx}(1/B)/R_0$, where SdH and commensurability oscillations, as well as a nonoscillating component, are clearly manifested. The dependence of $\Delta R_{SdH}(1/B)/R_0$ (Fig. 3b), obtained by subtracting commensurability oscillations and the nonoscillating component from the experimental curve, shows that no modulation of SdH oscillations takes place in our lattices. The behavior of the amplitude of SdH oscillations is well described by Eq. (5) with $A_{SdH} = 0.85$, $V_0 = 0$, and $\tau_q = 2.3$ ps. This means that SdH oscillations in the lattices under study behave as in a 2D system without potential modulation. The comparison of the dependences shown in Figs. 3b and 4a suggests that the amplitude of one-dimensional modulation of the potential in these lattices is $V_0 < 0.35$ meV.

The insignificant modulation of the amplitude of SdH oscillations in the studied lattices (thick line in Fig. 4a) means that the role of Landau bands in the modification of the electron spectrum can be taken into account by introducing additional Landau level broadening depending on $1/B$. In fields $B$ where $|V_B| < 0.3827\hbar\omega_c$ ($B > 0.04$ T for $V_0 < 0.35$ meV), this additional broadening can be taken into account by introducing an effective quantum lifetime $\tau_q^* = \tau_q^0 J_0(2\pi V_B/\hbar\omega_c)$. The dependence of $R_{SdH}/R_0$ on $1/B$ calculated by Eq. (5) with $\Delta D/D_0 = -2\exp(-\pi/\omega_c\tau_q^*)\times\cos(2\pi E_F/\hbar\omega_c)$ and $\tau_q^0 = 2.3$ ps is shown in Fig. 4b. This dependence is similar to the dependence calculated by Eq. (5) with $\Delta D/D_0 = -2J_0 \times (2\pi V_B/\hbar\omega_c)\exp(-\pi/\omega_c\tau_q)\cos(2\pi E_F/\hbar\omega_c)$ (Fig. 4a), which justifies the introduction of $\tau_q^* = \tau_q^0 J_0 \times (2\pi V_B/\hbar\omega_c)$ to take into account the additional broadening of Landau levels in a weak one-dimensional periodic potential.

The behavior of Zener oscillations of the differential resistance in an unmodulated 2D electron system under the condition $2R_c eE_{dc}/\hbar\omega_c \gg 1$ is determined by the expression [14]

$$\Delta r_{HIRO}/R_0 \approx A_{HIRO}\exp(-2\pi/\omega_c\tau_q) \times\cos(4\pi R_c eE_{dc}/\hbar\omega_c), \quad (6)$$

where $A_{\rm HIRO}$ is a dimensionless parameter of the order of unity. To take into account the effect of additional broadening of the Landau levels in a weak one-dimensional periodic potential, we replace $\tau_q$ in Eq. (6) by the effective quantum lifetime $\tau_q^* = \tau_q^0 J_0(2\pi V_B/\hbar\omega_c)$:

$$\Delta r^*_{\rm HIRO}/R_0 \approx A_{\rm HIRO}\exp(-2\pi/\omega_c\tau_q^*) \times \cos(4\pi R_c e E_{\rm dc}/\hbar\omega_c). \quad (7)$$

Like Eq. (5), this formula is valid only in the case of $|V_B| < 0.3827\hbar\omega_c$.

Figure 5a shows the calculated dependences of $\Delta r_{\rm HIRO}/R_0$ (thin line) and $\Delta r^*_{\rm HIRO}/R_0$ (thick line) on $1/B$ calculated by Eqs. (6) and (7) for unmodulated and modulated 2D electron gases, respectively. The thick and thin lines in Fig. 5b show the difference between the calculated $1/B$ dependences of $\Delta r^*_{\rm HIRO}/R_0$ and $\Delta r_{\rm HIRO}/R_0$ and the experimental dependence, respectively. There is good agreement between the theoretical and experimental curves. The times $\tau_q$ and $\tau_q^0$ were used as the fitting parameters. The dependence of $\Delta r_{\rm HIRO}/R_0$ on $1/B$ is described with $\tau_q = 4$ ps. In fact, this is the averaged value for the dependence of $\Delta r^*_{\rm HIRO}/R_0$ on $1/B$, whose behavior is specified by $\tau_q^0 = 4.6$ ps. This means that the latter value determines the behavior of Zener oscillations in a modulated 2D electron gas.

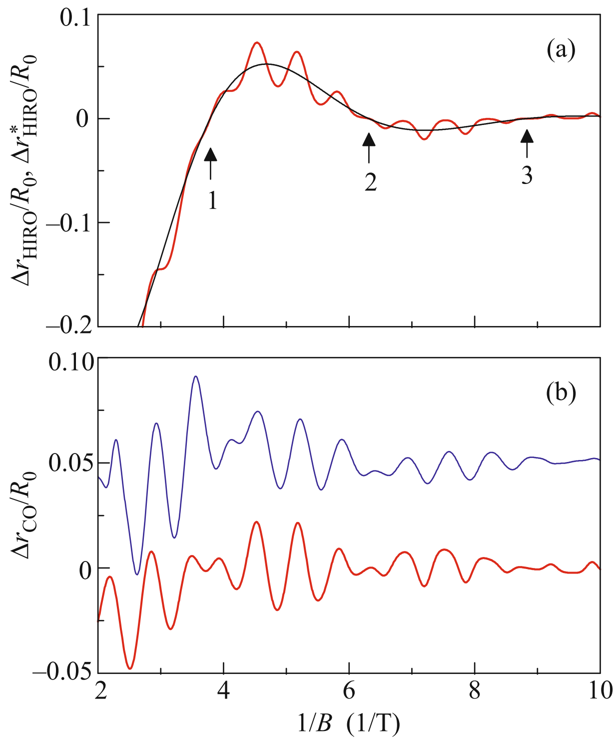


**Fig. 5.** (Color online) (a) (Thin line) Ratio $\Delta r_{\rm HIRO}/R_0$ versus $1/B$ calculated by Eq. (6) with the parameters $A_{\rm HIRO} = 1$, $I_{\rm dc} = 80$ μA, and $\tau_q = 4$ ps and (thick line) $\Delta r^*_{\rm HIRO}/R_0$ calculated by Eq. (7) with the parameters $A_{\rm HIRO} = 1$, $I_{\rm dc} = 80$ μA, $V_0 = 0.35$ meV, and $\tau_q^0 = 4.6$ ps. The arrows indicate the nodes of the beats in commensurability oscillations. (b) (Thin line) Experimental ratio $\Delta r_{\rm CO}/R_0$ versus $1/B$ for $T = 1.6$ K and $I_{\rm dc} = 80$ μA; the curve is shifted upwards by 0.05. (Thick line) $\Delta r_{\rm CO}/R_0 = \Delta r^*_{\rm HIRO}/R_0 - \Delta r_{\rm HIRO}/R_0$ versus $1/B$ calculated by Eqs. (6) and (7) with the parameters $A_{\rm HIRO} = 1$, $I_{\rm dc} = 80$ μA, $V_0 = 0.35$ meV, $\tau_q^0 = 4.6$ ps, and $\tau_q = 4$ ps.

The quantum times $\tau_q = 2.3$ ps and $\tau_q^0 = 4.6$ ps determined from the comparison of experimental and theoretical dependences of the amplitudes of SdH and Zener oscillations on the inverse magnetic field are different because Eq. (6) is valid only under the condition $2R_c eE_{\rm dc}/\hbar\omega_c \gg 1$. In our case, this condition is not satisfied. However, good agreement between the experimental and calculated dependences presented in Fig. 5b indicates that the observed interference between the resistance oscillations induced by a constant Hall electric field and the commensurability oscillations is caused by the additional broadening of Landau levels in a 2D electron gas with one-dimensional periodic modulation.

In summary, we have studied nonlinear magnetotransport in a high-mobility 2D electron gas with one-dimensional periodic modulation. The modulation potential was imposed by a set of metal strips formed on a planar surface of a selectively doped GaAs/AlAs heterostructure. The magnetic-field dependences of the differential resistance at a temperature of 1.6 K in lattices with a period of $a \approx$ 200 nm were investigated. It was found that oscillations in the differential resistance induced by a constant Hall electric field in a 2D system with one-dimensional periodic potential modulation interfere with commensurability oscillations. The experimental data obtained can be qualitatively explained by the modification of the energy spectrum of electron states in a one-dimensional periodic potential. It was shown that the modification of the spectrum can be taken into account by introducing an effective quantum lifetime depending on the inverse magnetic field.

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