A New Type of Magnetoresistance Oscillations: Interaction of a Two-Dimensional Electron Gas with Leaky Interface Phonons

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We report a new type of oscillations in magnetoresistance observed in high-mobility two-dimensional electron gas (2DEG) in GaAs-AlGaAs heterostructures. Being periodic in $1/B$ these oscillations appear in weak magnetic field ($B < 0.3$ T) and only in a narrow temperature range (3 K $< T <$ 7 K). Remarkably, these oscillations can be understood in terms of magneto-phonon resonance originating from the interaction of 2DEG and leaky interface-acoustic phonon modes. The existence of such modes on the GaAs-AlGaAs interface is demonstrated theoretically and their velocities are calculated. It is shown that the electron-phonon scattering matrix element exhibits a peak for the phonons carrying momentum $q = 2k_F$ (k_F is the Fermi wave-vector of 2DEG).

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There are several types of transverse magnetoresistance oscillations which exist in in both two- and three-dimensional homogeneous electron gases. The most common of them are Shubnikov de-Haas (SdH) oscillations, which arise due to periodic change of the density of states at Fermi level E_F in a magnetic field B. They become more pronounced with decreasing temperature. The magneto-phonon resonance (MPR) [1,2] is another source of oscillations, which arises from the absorption of bulk longitudinal optic phonons. These resonances appear under the condition $\omega_c = l\omega_o$, where $\omega_c = eB/mc$ and ω_o are the cyclotron and the optical phonon frequencies respectively, l is an integer, and m is an effective mass of carriers. These oscillations are only seen at relatively high temperatures (100-200K). Both SdH and MPR are periodic in $1/B$. However, MPR is independent of the electron density, while a period of SdH depends on density as $n_e^{2/D}$, where $D = 1, 2, 3$ is space dimensionality.

In this Letter we report on a new type of magnetoresistance oscillations, unrelated to either of the above origins, discovered in high-mobility GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructures [3]. Being periodic in $1/B$, these novel oscillations appear in a weak magnetic field ($B < 0.3$ T) and only in a narrow temperature range (3 K $< T <$ 7 K). Moreover, these oscillations have so far been observed only in 2DEG with a low-temperature mobility $\mu \geq 2 \times 10^6$ cm^2/Vs. Remarkably, the effect can be understood in terms of magneto-acoustic phonon resonance (MAPR) originating from the interaction of 2DEG with leaky interface-acoustic phonon (LIP) modes. Following the experimental data we present the results of theoretical calculations, demonstrating the existence of LIP modes at the GaAs-AlGaAs interface. Using the bulk moduli of the host lattices we calculate the velocity u of these modes, which is found to be in good agreement with experiment. Analysis of the electron-phonon scattering matrix element shows that, in the presence of the weak B field, 2DEG is interacting selectively with the interface phonons carrying momentum $q = 2k_F$, where k_F is the Fermi momentum of the 2DEG at zero B field. The condition for resonant absorption or emission of the LIP by the 2DEG is then given by

$$2k_F u = l\omega_c, \quad l = 1, 2, 3, \ldots . \tag{1}$$

We claim that Eq. (1) determines the values of magnetic field for the maxima in new magneto-oscillations. It is important, however, that the novel oscillations are exclusive property of 2DEG, and the selection rule $q = 2k_F$ assumes that q is a lateral momentum of the phonon. Therefore bulk phonon can not account for the MAPR, since its q_z component would destroy the condition (1). Eq. (1) shows that oscillations are periodic in $1/B$ and their period is proportional to $\sqrt{n_e}$.

Our samples are lithographically defined (width 50 μm or 100 μm) Hall bars of high-mobility GaAs-$Al_{0.3}Ga_{0.7}As$ wafers grown by MBE. While similar oscillations have been observed in a variety of samples, here, we present the data from one specimen with an electron density $n_e = 2.17 \times 10^{11}$ cm^{-2} and a mobility $\mu \approx 3 \times 10^6$ cm^2/Vs, achieved by a brief illumination from a red light-emitting diode at $T = 4$ K. The distance between the electrons and the Si doping layer is $d_s \approx 700$Å. Experiments have been done in a variable-temperature liquid ^{4}He cryostat equipped with a superconducting magnet, employing a standard low-frequency (3 to 7 Hz) lock-in technique to measure the magnetoresistance.

In Fig.1.a we show low-field magnetoresistivity $\rho_{xx}(B)$ measured at $T = 4$ K. In addition to the damped SdH effect commonly seen in a 2DEG at this temperature, the trace reveals another oscillatory structure that appears only at lower field $B < 0.3$ T. The arrows next to the trace indicate the first three (indexed as l = 1, 2,

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3) $\rho_{xx}(B_l)$ maxima in this oscillatory structure. Such a structure may, in principle, arise from the SdH effect of electrons occupying the upper subband of the potential well. Since inter-subband separation in GaAs-AlGaAs heterostructure is typically > 200 K, and E_F in our sample is about 80 K we do not expect considerable population of the second subband at low temperatures. Furthermore, corresponding Landau splitting in GaAs ($\hbar\omega_c \approx$ 2K at 0.1T) is too small for SdH to be observed at 4 K. Finally, the disappearance of the oscillations at lower temperature (see Fig.2) is inconsistent with SdH and therefore we conclude that SdH can not account for the observed oscillatory structure.

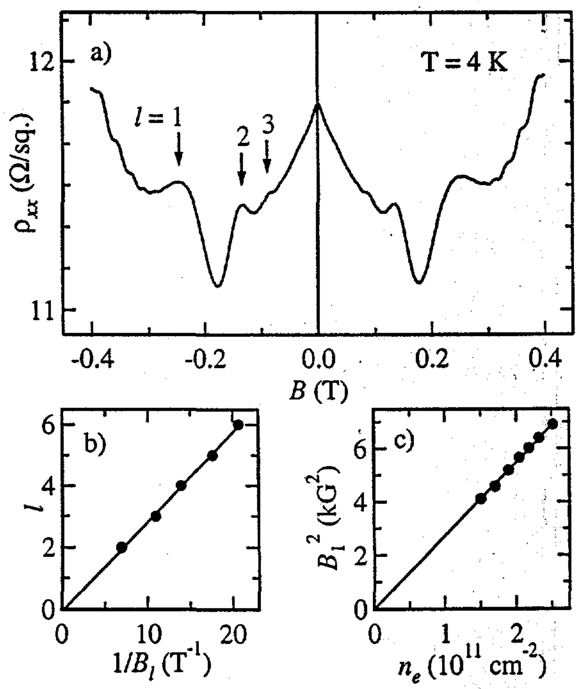

FIG. 1. a) Magnetoresistivity at T = 4 K showing new series of oscillations beyond SdH effect at $B < 0.3$ T; maxima for l = 1,2,3 are marked by arrows; b) l vs. $1/B_l$ (circles) and fit (line) using Eq. (1) reveals $u = 3.0$ km/s; c) B_1^2 vs. n_e.

Instead, we analyze the oscillations in terms of MAPR [Eq. (1)]. From $d^2\rho_{xx}(B)/dB^2$ of the trace in Fig.1.a, we arrive at a plot of l vs. $1/B$, shown in Fig.1.b. It demonstrates the periodicity of the oscillations in reciprocal magnetic field in accordance with Eq. (1). Linear fit to the data (solid line) generates the phonon velocity $u = 3.0$ km/s. In Fig.1.c we plot the square of the magnetic field position of the primary maximum, *i.e.*, $B_{l=1}$ as a function of n_e changed by applying the bias to the front gate of our sample. Since $k_F = \sqrt{2\pi n_e}$, observed linear dependence implies $B_1 \propto k_F$ as prescribed by Eq. (1). Linear fit (solid line) leads to the the same value of $u = 3.0$ km/s.

To further support of the MAPR scenario, we present the $\rho_{xx}(B)$ traces at several temperatures ranging from 1.9 K to 9.1 K in Fig.2.a. While SdH gradually diminishes as T increases, MAPR oscillations are best developed at $T \sim$ 4-6 K, and are strongly damped at both higher and lower temperatures. We also note (see Fig2.b) that zero-field resistivity $\rho_{xx}(0)$ grows linearly with T implying that acoustic-phonon scattering dominates the electron mobility (so called, Bloch-Gruneisen regime) in this temperature range [7]. It is interesting, that the lowest temperature for this linear behavior can be estimated from the energy of acoustic phonon with $q = 2k_F$ [7], *i.e.* $k_BT = \hbar u(2k_F)$ which for our system is estimated to be 5.1 K, the temperature where the oscillations are best observed.

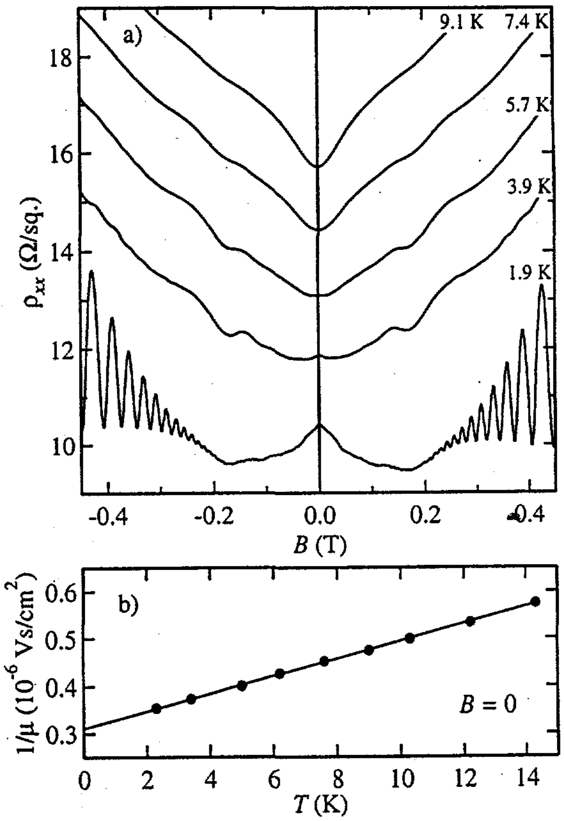

FIG. 2. a). Magnetoresistivity at different T showing that oscillations are best developed around 4 K and are strongly suppressed at higher and lower temperatures; b). Linear dependence of inverse zero-field mobility vs. T demonstrates Bloch-Gruneisen regime

We devote the rest of the paper to the discussion of the theoretical model based on scattering of the 2DEG by leaky-interface phonons. The possibility for waves propagating along an interface was demonstrated by Stoneley [4]. He derived the dispersion relation for speed of propagating wave, assuming that both media are isotropic. It has been found that for some values of parameters a localized mode at the interface, so called Stoneley wave, can exist. The frequency of Stoneley waves (SW) is a linear function of the wave vector: $\omega = u_s q$, and its speed u_s must lie between the speeds of surface wave u_{sur} and transverse wave u_t in the denser medium, i.e.

$u_{sur} < u_s < u_t$. The SW exist only for rather restrictive conditions on the bulk elastic properties of the two media. One can see that the interface we consider, namely $Al_{0.3}Ga_{0.7}As$-GaAs cut perpendicular to (001) direction does not possess SW at any reasonable values of the parameters in an isotropic approximation. It is worth to note that Stoneley dispersion relation admits other solutions, which correspond to leaky interface modes that are attenuated as they propagate along the interface due to the radiation of energy into one or the other of the two media in contact, or both. Since the elasticity theory does not take into account any irreducible losses of energy, this radiation of energy away from the interface leads to the attenuation of a leaky wave in the plane of interface. As a consequence the values of frequency and velocity become complex: $u = \omega/q = u_R + iu_I$ with $u_I \ll u_R$. Until now leaky waves were detected in surface acoustic [5] and in GaAs-AlAs super-lattices for optical phonon branches [6]. The amplitude of such waves grows exponentially with increasing distance in the direction perpendicular to the interface. However, it does not prevent from considering them as regular phonons at the interface. A nice physical explanation of this fact can be found in Ref. [8].

General anisotropic case has been considered numerically in Ref. [9] for an interface between Cu and other Cu-like hypothetic crystal. Another method for calculation of interface phonons is based on surface Green function matching [10]. A good review on the theory of both surface and interface phonons can be found in Ref. [11].

We have performed the calculations of LIP modes for the $Al_{0.3}Ga_{0.7}As$-GaAS interface [12]. Using elastic moduli of the bulk materials [13] we have derived the anisotropic dispersion relation for LIP velocity in two directions of high symmetry, namely [110] and [100]. The slowest LIP mode has the complex velocity $u = 3.1(3.2) + i\,0.08(0.09)$ km/s in direction [110]([100]) that is in good agreement with our experimental value of 3.0 km/s derived using Eq. (1). This result also suggests rather weak anisotropy of the interface wave. The study of group velocities of these waves shows that the energy flows towards the bulk $Al_{0.3}Ga_{0.7}As$, forming a glacing angle of ~ 10 deg with the interface. The next upper LIP branch with the real part of velocity $4.7\,km/s$ and stronger attenuation is strongly suppressed at the temperature of our experiments and is ignored in further analysis. Since $u_R([110]) \approx u_R([100])$, we suggest the isotropic behavior of the slowest LIP.

To calculate the transverse conductivity due to the scattering of 2DEG on LIP we employ two-dimensional analogue of the formula, first derived by Titeica [14]:

$$\sigma_{xx} = \frac{4\pi e^2}{Am^2kT\omega_c^2} \sum_{n,n'} \sum_{k_y,k_y'} \sum_{q_x,q_y} |I_{nn'}(q\lambda)|^2 q_y^2 |C(q)|^2 \times N_l f_n(1-f_{n'}) \delta_{k_y-k_y'+q_y} \delta(\hbar\omega_c(n'-n) - qu). \quad (2)$$

Here A is the area, $N_l = (\exp(\hbar\omega/kT)-1)^{-1}$, $f_n = (\exp((E_n-\mu)/kT)+1)^{-1}$, $\lambda = \sqrt{\hbar c/eB}$ is the magnetic length, and $|C(q)|^2 \equiv v(q)/A$ is the normalized on area square modulus of 2DEG-LIP interaction, which has a power dependence on q. This formula can be interpreted in the following way. The electrons occupy Landau Levels (LLs) $E_n = \hbar\omega_c(n+1/2)$ with the degeneracy of $1/2\pi\lambda^2$ per unit area. The eigenfunctions of the system are a product of a plane wave in y direction and oscillatory wave function, centered at the position $x_0 = -c\hbar k_y/eB$: $\Psi = \exp(ik_y y)\phi_n(x-x_0)$. In the absence of scattering the electric current may flow only in y-direction, providing the Hall effect. A transverse conductivity appears because an electron transfers momentum $q_y = k_y' - k_y$ to a scatterer. It is equivalent to the jump in x-direction at a distance $\Delta x_0 = c\hbar q_y/eB$. In Eq. (2) this physics is applied to electron scattering on the interface phonons.

The mechanism of the 2DEG-LIP interaction, which may be either deformation potential or piezoelectric interaction, is not particularly important for the explanation of the novel magneto-oscillations. We also include in $C(q)$ the part of the matrix element connected with the wave function perpendicular to the plane that can be taken in the Fang-Howard approximation [15]. Since the amplitude of the LIP waves increases towards $Al_{0.3}Ga_{0.7}As$, where the electron wave function is vanishing, this amplitude's growth does not prevent us from the calculation of the matrix element in the direction perpendicular to the 2DEG.

If the interface phonon has no attenuation, the square of matrix element $I_{nn'}$ is given by [15]

$$|I_{n,n+l}(b)|^2 = \left| \int_{-\infty}^{+\infty} e^{iq_x x} \phi_n(x-x_0)\phi_{n+l}(x-x_0')\,dx \right|^2 = \frac{n!}{(n+l)!} \left(\frac{b^2}{2}\right)^l e^{-\frac{b^2}{2}} \left[L_n^l\left(\frac{b^2}{2}\right)\right]^2, \quad (3)$$

where $b = q\lambda$ and $L_n^l(x)$ is the generalized Laguerre polynomial.

Substituting summation over momentums by integration in Eq. (2) one obtains

$$\sigma_{xx} = \frac{e^2/h}{mkT\omega_c} \sum_{n,l} N_l f_n(1-f_{n+l}) \times \int_0^\infty dq\, q^3 v(q) \left|I_{n\,n+l}(q\lambda)\right|^2 \delta(\omega_c l - qu). \quad (4)$$

Taking into account the imaginary part of the LIP frequency, $\omega = q(u_R + iu_I)$, we can substitute δ-function in Eq. (4) by Gaussian distribution with appropriate dispersion $\sigma = qu_I$. Since the dispersion is small we can set $q = \omega_c l/u_R$ everywhere except for the strongly oscillating function $|I_{nl}(q\lambda)|^2$. Then after averaging we obtain for transverse conductivity

$$\sigma_{xx} = \frac{e^2/h}{mu\omega_c kT} \sum_{l,n} v\left(\frac{\omega_c l}{u}\right) F_{nl} N_l f_n(1-f_{n+l}), \quad (5)$$

where the function F_{nl} can be expressed in series over Hermit polynomial of imaginary argument:

$$F_{nl} = \frac{(\omega_c l/u)^3}{\sqrt{1+\alpha^{-1}}} \exp\left(-\frac{\alpha}{1+\alpha}\frac{\hbar\omega_c l^2}{2mu^2}\right)\sum_{k,j}^{n}\frac{n!(-1)^l}{(n+l)!k!j!}$$

$$\binom{n+l}{n-k}\binom{n+l}{n-j}\frac{H_{2(k+j+l)}\left(il\sqrt{\frac{\hbar\omega_c}{2mu^2}}\frac{\alpha}{\sqrt{1+\alpha}}\right)}{[2\sqrt{1+\alpha}]^{2(k+l+j)}}, \quad (6)$$

with $\alpha = (u/\sigma\lambda)^2$. Hereafter, we assume that u is the real part of LIP velocity. In Fig. 3 we plot F_{nl} for $n = 17$ and $l = 1$ as a function of B for LIP with $\sigma = \omega_c u_I/u_R$ (solid line) and in the limit $\sigma = 0$ (dashed line).

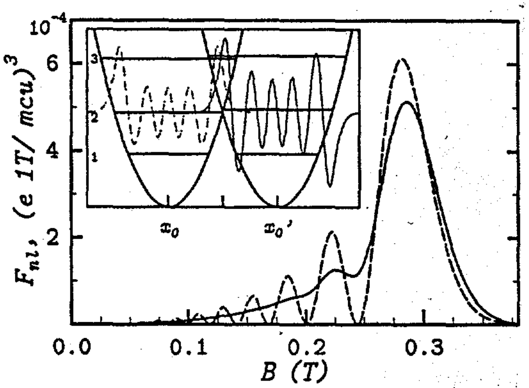

FIG. 3. $F_{17,1}(B)$ in the limit $\sigma = 0$ (dashed line) and for LIP (solid line). The insert schematically shows the origin of the strongest peak in function $F_{nl}(B)$.

As we can see, once attenuation is introduced, there remains only one strong peak at the position of the last maximum of the square matrix element (3) that corresponds to the selection rule for the phonon wave vector

$$q\lambda \approx 2\sqrt{2n}. \quad (7)$$

This is an important result of our work. It can be interpreted from the following semi-classical consideration (see the insert in Fig. 3). Let us consider $n \sim n' \gg 1$. Since the square of the matrix element in Eq. (3) depends on q only, we can put $q_x = 0$. Then the integrand in (3) is an overlap of two oscillatory wave functions shifted with respect to each other. In the vicinity of the turning point the wave function has always maximum since the momentum is small and the particle spends the most part of its time there. There are three possibilities. Cases 1 and 3 in the inset show situations when turning points are apart from each other, and case 2 occurs when turning points coincide in space. Obviously, in case 2 the overlap integral has a maximum. It happens if $m\omega_c^2(\Delta x_0)^2/8 = n\hbar\omega_c$, that is equivalent to the condition (7).

Furthermore, Fermi distributions in (5) restrict the values of n to the neighborhood of the upper filled LLs $n = n_F \approx E_F/\hbar\omega_c$ and then Eq. (7) reduces to $q = 2k_F$. Since $\omega_c l = qu = 2k_F u$ the maximum in $F_{nl}(B)$ gives rise to oscillations in $\rho_{xx}(B)$ that are periodic in $1/B$ with a period $\Delta(1/B) = e/(2k_F umc)$, as observed in experiment. At low temperatures the oscillations disappear simply because the interface phonons are bosons, and they are not excited. This is the most important difference between these novel phenomenon and ShD oscillations. At high temperatures the smearing of the LLs becomes important (due to increase of scattering by acoustic bulk phonons) and oscillations disappear as well.

In conclusion, we have discovered a new type of magneto-oscillations in a high-mobility 2DEG and interpreted them as a magneto-acoustic phonon resonance with leaky interface acoustic phonones. Owning to the dispersion of the acoustic modes, it was *a prior* belief that only optical modes, and not the acoustic modes, may be used for phonon spectroscopy in a 2DEG. Our work may open up a new way for phonon spectroscopy in 2DEG, including resonance of ballistic interface phonons with correlated electronic states in GaAs-AlGaAs heterostructures.

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