PHYSICAL REVIEW B, VOLUME 64, 201311(R)

Shubnikov–de Haas-like oscillations in millimeterwave photoconductivity in a high-mobility two-dimensional electron gas

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(Received 27 April 2001; published 30 October 2001)

Millimeterwave photoconductivity in a high-mobility GaAs-Al$_x$Ga$_{1-x}$As two-dimensional electron gas exhibits giant amplitude oscillations in a weak magnetic field. These oscillations resemble the Shubnikov–de Haas effect but their period is determined by ω/ω_C, where ω and ω_C are the millimeterwave and cyclotron frequencies, respectively. The major observations can be explained in terms of Landau-level transitions between spatially shifted oscillators. A $2k_F$ momentum transfer is accompanying the transition where k_F is the electron Fermi wave number.

DOI: 10.1103/PhysRevB.64.201311 PACS number(s): 73.50.Pz, 73.21.−b

The electrodynamical response of a quantum Hall system is a fundamental issue[1] in correlation physics but has proven difficult to access experimentally. Among the established techniques, cyclotron resonance (CR) is a powerful tool to study Landau level (LL) spectra and electron-electron interactions in a two-dimensional electron system (2DES).[2] On the other hand it is textbook knowledge that in a homogeneous 2DES in which the translational symmetry is preserved, a long-wavelength radiation field can couple only to the center-of-mass motion but not to the relative motion of electrons. This principle, known as Kohn's theorem,[3] forbids the observation of electron-electron interaction effects in a 2DES by standard CR. Once the translational symmetry is broken or a finite momentum transfer is introduced in the process, other degrees of freedom can be excited thereby allowing for the detection of collective modes in the system, such as finite-wave-vector magnetoplasmons.[4] Impurities and short-range scatterers play significant roles in providing the momentum transfer mechanism in a 2DEG.[5] Recently, the interplay between a long-range smooth potential and short-range strong scatterers has been studied in relation to magnetotransport in a very high mobility 2DES in GaAs-Al$_x$Ga$_{1-x}$As heterostructures.[6,7] Finite momentum response is also relevant to the millimeterwave spectroscopy of 2DES, which often translates to the CR in a weak magnetic field, electron spin resonance,[8] long-wavelength magnetoplasmon,[9] and dynamical response of many-electron states in quantum Hall systems.[10]

In this paper we report on the first observation of impurity-assisted CR detected by millimeterwave photoconductivity (PC) in a high-mobility 2DES in a GaAs-Al$_x$Ga$_{1-x}$As heterostructure.[11] We define the PC signal as the difference between magnetoresistances with and without millimeterwave illumination. We note that PC resonance related to CR in high magnetic field and in far-infrared frequency range has been well known in the literature.[12,13] Unusual features appear in our millimeterwave experiment. In a weak magnetic field (B), the PC signal shows periodic (in $1/B$) oscillations which resemble the regular Shubnikov–de Haas effect (SdH). However the period of these oscillations is governed by the ratio of ω/ω_C, where ω and ω_C are, respectively, the millimeterwave and cyclotron frequencies. Unlike the standard CR which results primarily from optical transitions between the adjacent LLs, the PC oscillations manifest transitions among a multiplet of LLs. As will be shown, such multiple CRs are only possible when a finite momentum transfer Δq is accompanying the transition. Specifically, $\Delta q=2k_F$, where k_F is the electron Fermi wave number in zero magnetic field. Such a momentum transfer is equivalent to a jump of electron orbit guiding center along the transverse direction, thereby causing a conductivity peak readily detectable by magnetotransport measurements. Possible sources of short-range scatterers responsible for Δq in our GaAs-Al$_x$Ga$_{1-x}$As heterostructures may include interface roughness or residual impurities. The effect described here bares similarities to the recently reported magnetoresistance oscillations in a 2DEG due to resonant absorption of leaky interface phonons.[14] However, in magnetophonon resonance both the required energy and momentum are provided by phonons.

Our samples are high-mobility ($\mu \geqslant 3.0\times10^6$ cm^2/Vs) 2DES in GaAs-Al$_x$Ga$_{1-x}$As heterostructures grown by molecular-beam epitaxy, having an electron density $n\approx2\times10^{11}$ cm^{-2}. Such parameters are obtained by a brief illumination from a red light-emitting diode at a temperature $T\approx4$ K. The distance from the Si doping sheet to 2D electrons is $d_s=70$ nm. Our primary specimens are lithographically-defined Hall bars (width $w=50$, 100, and 200 μm), but similar results have been obtained from specimens of square (1 mm$\times$1 mm and 5 mm$\times$5 mm) geometry. Coherent, linearly polarized millimeterwaves are provided by a solid state source of tunable frequency f from 30 to 150 GHz (1.5 to 7.5 K), and are sent down to the experiment via an over-sized waveguide. Typical output power of the source is from 10 mW to 100 mW and can be tuned by an attenuator. The specimen is immersed in a ^{3}He coolant kept at a constant temperature ranging from 0.3 to 2.0 K. The mutual orientation of the waveguide, specimen, and magnetic field from a superconducting magnet corresponds to Faraday configura-

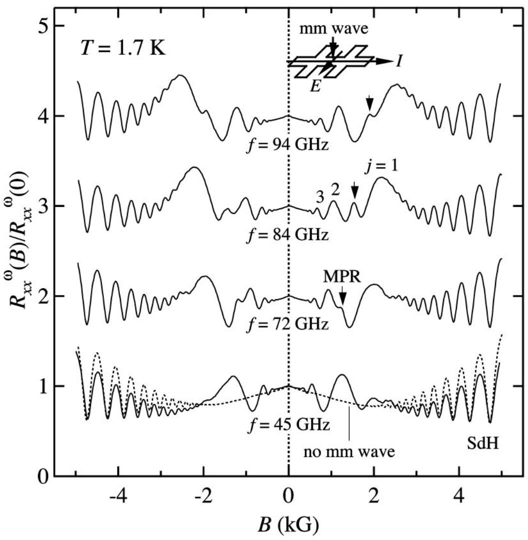

FIG. 1. Normalized magnetoresistance from 200 μm Hall bar with millimeterwave illumination on (solid lines) and off (dotted line) for selected frequencies. The traces are offset vertically for clarity. The arrows mark the magnetoplasmon resonance signal. The difference in SdH amplitudes between illumination on ($T \approx 1.7$ K) and off ($T \approx 1.5$ K) traces is due to a nonresonant heating of the 2DEG by the millimeterwave radiation.

tion; the excitation current typically flows perpendicularly to the millimeterwave polarization. Magnetoresistance is measured in the same way as it is done in standard magnetotransport, i.e., employing low-frequency (7–17 Hz) lock-in detection, in sweeping B and at constant T, except that the sample is under *continuous* illumination with millimeterwave radiation of fixed frequency and power.

We first present in Fig. 1 normalized magnetoresistance traces, which reveal the PC signal $\Delta R_{xx}^{\omega}(B) = R_{xx}^{\omega}(B) - R_{xx}^{0}(B)$ due to millimeterwave illumination. Here, the data were taken from a 200 μm Hall bar at fixed $T = 1.7$ K, for selected millimeterwave frequencies $f = \omega/2\pi = 45$, 72, 84, and 94 GHz. For comparison, the "dark" trace (dotted line, $T = 1.5$ K) is also shown, revealing *only* regular SdH above an onset field $B_{\mathrm{SdH}} \approx 2$ kG. In general, $\Delta R_{xx}^{\omega}(B)$ alternates in sign so as to form an oscillatory structure periodic in $1/B$ (see Fig. 2). As f increases, this oscillatory structure shifts toward the higher B range in an orderly fashion, preserving the $1/B$ periodicity. The number of resolved oscillations typically grows with increasing f, reaching as high as 10 for $f \geqslant 100$ GHz, but the onset field $B_{CR} \approx 0.3$ kG, at which these oscillations appear, remains unchanged.

In addition to this oscillatory structure, a distinct ΔR_{xx}^{ω} peak (arrows) emerges for $f \gtrsim 60$ GHz. With increasing f it travels from one CR peak towards another, thus manifesting stronger frequency dependence. We relate this peak to low-frequency collective excitation;[9] the B dependence of this peak is in excellent agreement with a magnetoplasmon mode having wave vector coupled to our Hall bar mesa ($q = 2\pi/w, w = 200$ μm). In contrast to Ref. 9, we do not observe any softening of the plasma frequency. As expected, the magnetoplasmon signal is absent in the square specimen where only the millimeter wavelength modes can be sustained. In the rest of the paper we shall focus on our central finding, namely the oscillatory structure in the PC signal.

Phenomenologically the PC oscillations can be interpreted in terms of high-order CR, i.e., the resonant transitions between nonadjacent LLs. In particular, the B positions of the maxima in this oscillatory structure satisfy a resonance condition in which the millimeterwave quantum equals the cyclotron energy $\hbar\omega_C = \hbar eB/m^*$ times an *integer multiple* j, where j is the difference between the indices of participating Landau levels:

$$\hbar\omega = j\hbar\omega_C \quad j = 1,2,3, \ldots . \tag{1}$$

A quantitative analysis of the PC signal shows exactly such a relation for the peak positions. In Fig. 2 we present low-field magnetoresistivity from the same sample under illumination for $f = 94$ GHz, and at a lower temperature $T = 0.4$ K. A striking similarity between the millimeterwave PC and the regular SdH is apparent. However, unlike the SdH whose period is determined by a ratio $E_F/\hbar\omega_C$, the period of PC oscillations is governed by an *external* energy scale introduced by the millimeterwave radiation, and does not depend on the Fermi energy, E_F. It is easily noticed that $\Delta R_{xx}^{\omega}(B)$ peaks satisfy the resonance condition (1). As examples, in the inset of Fig. 2 we plot the multiplicity index j versus $1/B$ for two selected frequencies of 55 GHz and 148.5 GHz. Here we include both the integer $j = 2,3, \ldots$ (maxima) and the half integer $j = 3/2, 5/2, \ldots$ (minima) and both appear to be well described by Eq. (1). From observed linear dependencies we deduce an electron effective mass $m^* = 0.068 m_0$ (m_0 is the free electron mass), which agrees well with the known value for band electrons in GaAs. Excellent agreement over the whole range of j is observed, leading to the conclusion that detected PC oscillations are caused by millimeterwave-induced transitions between pairs of nonadjacent LLs, or high-order CRs.

Although signatures of "high-harmonic" transitions in CR have been previously seen in high-B transmission experiments for 2D electrons on Si surface[15,16] and explained via

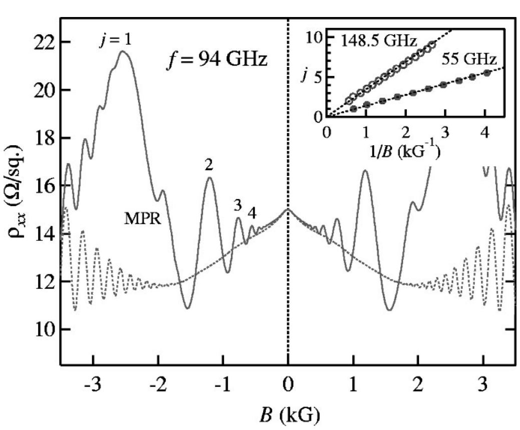

FIG. 2. Magnetoresistivity with millimeterwave ($f = 94$ GHz) illumination on (solid) and off (dotted) at $T = 0.4$ K. Inset shows a plot of the multiplicity index j versus $1/B$ for $f = 55$ GHz and $f = 148.5$ GHz to reveal an electron effective mass $m^* \approx 0.068 m_0$.

short-range scattering potentials,[17] the amplitude of even the second-order CR remained rather weak as compared to the fundamental. On the contrary, our PC measurements have revealed up to the 10th ‘‘harmonic’’ in our high-mobility 2DES.

The appearance of such oscillations is quite unexpected and difficult to explain on first thought. Fundamentally, within a simple harmonic oscillator model high-order CRs are forbidden. This is because the dipole-dipole matrix elements are nonvanishing only for transitions between adjacent LLs; all other transitions are not allowed. Moreover, within the same model the magnetoresistance corrections resulting from LL transitions are expected to be rather small.[13] Notice that the PC signal is usually considered as a bolometric effect, i.e., resonant heating. Apparently both the extraordinary sensitivity of the PC signal to the high harmonics and their giant amplitudes cannot be accounted for by the abovementioned simple harmonic oscillator model. We therefore propose the following scenario in which the giant amplitude PC oscillations can be naturally explained in terms of LL transitions between *spatially shifted* oscillators, with a $2k_F$ momentum transfer accompanying the transition.

In Landau gauge a wave function of a 2D electron in a magnetic field $\mathbf{B}=B\cdot\hat{z}$ is a product of a plane wave in the y direction and an oscillatory wave function, centered at the guiding center $x_0=-\hbar k_y/eB$: $\Psi=\exp(ik_y y)\phi_N(x-x_0)$, where N is the LL index. If free of scattering, the electric current flows only in the y direction, giving rise to the Hall effect. A transverse conductivity appears because an electron transfers wave vector $q_y=k_y'-k_y$ to a scatterer. This momentum change is equivalent to a spatial jump in the x direction by a distance $\Delta x_0=-\hbar q_y/eB=-l_B^2 q_y$, where l_B is the magnetic length. The corresponding correction to the resistivity is proportional to the square of matrix element $I_{N,N+j}$, which is given by[14]

$$I_{N,N+j}=\int_{-\infty}^{+\infty} e^{iq_x x}\phi_N(x-x_0)\,\phi_{N+j}(x-x_0')\,dx. \qquad (2)$$

In fact, $I_{N,N+j}$ depends on q only, so we can put $q_x=0$ and the integrand in Eq. (2) becomes an overlap of two harmonic oscillator wave functions shifted with respect to each other. Since in our case of weak magnetic fields $N\sim N+j\gg 1$, the following semiclassical discussion is appropriate. To begin with, we notice that the oscillator wave function always has a maximum at the classical turning point where the momentum is small and where the particle spends most of its time. Alternatively, we can model the distribution probability in the initial and final states $|\phi_N|^2$ with finite width rings of radius $R_C^N\approx R_C^{N+j}\approx\hbar k_F/eB=l_B^2 k_F$. Now, if one continuously varies the spatial separation between the rings, the overlap integral in Eq. (2) has a maximum when $x_0-x_0'\approx R_C^N+R_C^{N+j}\approx 2R_C^N$, as shown in Fig. 3. In momentum space this translates to

$$\Delta q_y\approx 2k_F. \qquad (3)$$

Therefore we conclude that the transition probability is maximized every time when the condition (3) is satisfied.

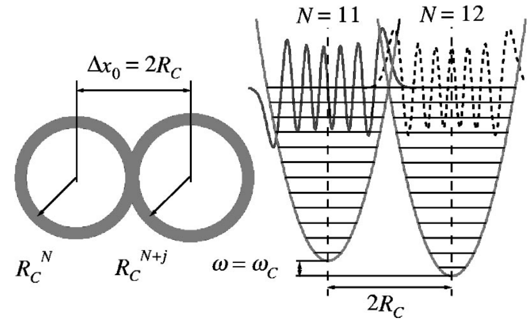

FIG. 3. Left: the electron orbits of the Nth and $N+j$th Landau levels are modeled by narrow rings; the maximum overlap occurs when $\Delta x_0\approx 2R_C^N$. Right: schematic representation for transition between the $N=11$ LL in initial orbit and the $N=12$ LL in shifted orbit, corresponding to $j=1$ peak in photoconductivity. In a sweeping magnetic field oscillation arise from coincidence between LLs close to the Fermi energy in two oscillators.

Once we accept this model based on momentum-transferred transitions between LLs in shifted oscillators, the oscillatory structure in the PC signal should be easy to understand. In a simplistic representation (Fig. 3), the LLs in the initial electron oscillator are uniformly up-shifted by $\hbar\omega$ due to the absorption of millimeterwave quanta. PC oscillations arise in a sweeping magnetic field according to the alignment of the LLs in the initial and final oscillators. In particular, coincidence of the LLs close to the Fermi energy opens up a scattering channel, giving rise to the conductivity peak as prescribed by Eq. (1). In principle, the PC minima can be accounted for as well, since maximum misalignment occurs when j takes half-integer values.

At $T=0$, only electrons which are close to the Fermi energy contribute to the conductivity. At finite T, the LLs acquire an effective width of $\sim kT$ but this should not significantly affect the transition probability as long as $kT\lesssim\hbar\omega$. Indeed, as shown in Fig. 4, the amplitudes of the CR oscillations do not change substantially from 0.5 to 1.5 K, whereas the SdH exhibits much stronger T dependence.

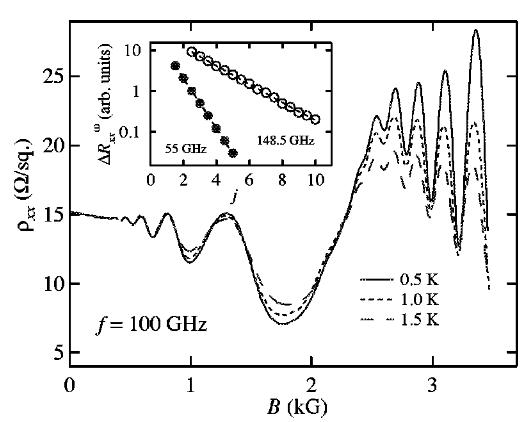

FIG. 4. Magnetoresistance traces under continuous illumination ($f=100$ GHz) are shown for several temperatures; temperature dependence of CR oscillations is considerably weaker as compared to that of SdH. Inset shows ‘‘Dingle’’ plots of CR oscillations for $f=55$ GHz (filled circles) and 148.5 GHz (open circles).

We comment on the role of weak magnetic field and that of short-range scatterers in PC experiments in our high-mobilty 2DES. It is self-evident that $2k_F$ momentum transfer leads to a stronger PC response in a weak field due to its l_B^2 dependence on the magnetic length. While remote ionized impurities in the dopant layer are generally considered the main source of electron scattering in high-mobility 2DEG, these long-range ($1/d_s \ll 2k_F$) scatterers are unlikely to participate in the $2k_F$ transfer processes. On the other hand short-range scatterers, such as interface roughness or residual impurities in the spacer, can readily accommodate the $2k_F$ momentum transfer. The role of short-range scatterers in high-mobility heterostructures has been recently addressed.[6] Indeed, the negative magnetoresistance seen in Fig. 2 is a strong evidence for the presence of such scatterers in our sample.

Empirically, the amplitude of the oscillations seems to obey a Dingle plot procedure, although from a theoretical point of view the validity of the SdH formalism in this case is uncertain. In the inset of Fig. 4 we plot the amplitude of CR oscillations as a function of multiplicity index j for $f = 55$ (148.5) GHz represented by solid (open) symbols. Both sets of data exhibit clear exponential behavior over two orders of magnitude and extending up to the 10th harmonic for higher frequency. Moreover, both data sets are fitted equally well (solid lines) to reveal the unique value of $\tau_{CR} = 13$ ps, which is about five times larger than $\tau_{\mathrm{SdH}} = 2.5$ ps [determined from a Dingle plot (not shown)] but less than scattering time $\tau_t = \mu m^*/e \approx 115$ ps. This is consistent with the lower onset field $B_{CR} \approx 0.3$ kG as compared to $B_{\mathrm{SdH}} \approx 2$ kG. It is well known[18] that density inhomogeneity contributes to an underestimate of the experimental value of τ_{SdH}. On the other hand, the photoresponse due to high-order CR can be viewed as a local effect (e.g., localized to several R_C) and, as such, be primarily sensitive to homogeneous broadening of LLs. As a result, this technique provides an insight on the homogeneous broadening of LLs, similarly to the transmission experiments.

In conclusion, we have discovered Shubnikov–de Haas-like oscillations in millimeterwave photoconductivity in high-mobility 2DES. We have explained the effect in terms of multiple, momentum-transferred transitions between LLs in shifted oscillators in a weak magnetic field. Based on the analogy between the electrons in a weak magnetic field and the composite fermions in a half-filled lowest LL, similar effect should be explored in the fractional quantum Hall effect regime.

We thank D. C. Tsui for encouragement and valuable discussions, M. E. Raikh, A. L. Efros, J. M. Worlock, and L. W. Engel for useful conversations. The work was supported in part by NSF Grant No. DMR-9705521 (M.A.Z. and R.R.D). R. R. D. would like to thank the Alfred P. Sloan Foundation for financial support. The work at Sandia was supported by the U.S. DOE under Contract No. DE-AC04-94AL85000.

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