Magneto-photon-phonon resonances in two-dimensional semiconductor systems driven by terahertz electromagnetic fields

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In this paper, we propose to study the magneto-photon-phonon resonance effects observed in terahertz (THz)-driven two-dimensional electron gases in strong magnetic fields. The photon energy of the THz electromagnetic radiations is on the scale of the cyclotron energy (induced by strong magnetic fields) and the LO-phonon energy so that (i) THz radiations will modify strongly the process of electron energy relaxation in the device structure; (ii) electrons can gain the energy from ac and dc driving fields through, e.g., absorption of the photons and lose the energy through, e.g., emission of the LO phonons; and (iii) resonant scattering will occur among different Landau levels (LL's) when a condition $M\omega_c+\omega=\omega_{\rm LO}$ is satisfied, where ω_c ($\omega,\omega_{\rm LO}$) is the cyclotron (photon, LO phonon) frequency and M is an index difference between two LL's. This leads to an enhancement of the resistivity and, consequently, to an enhanced rate of the absorption of the THz electromagnetic radiation in the sample systems. Varying the photon and cyclotron frequencies will result in a series of *magneto-photon-phonon resonances* observed in the dc resistivity (or conductivity) and/or in the optical absorption coefficient. We have presented a detailed theoretical study to observe this quantum resonance effect. [S0163-1829(96)10731-1]

I. INTRODUCTION

Far-infrared (FIR) or terahertz (THz) electromagnetic waves are of paramount importance in applications such as radio astronomy, environmental monitoring, plasmon diagnostics, and certain types of laboratory spectroscopies.[1] In recent years, the generation, propagation, and detection of THz electromagnetic radiation has become a fast-growing research field in photonics, optoelectronics, and condensed-mater physics communities. It has been realized that $Al_xGa_{1-x}As/GaAs$-based low-dimensional electron systems (LDES's) can be used as THz radiation detectors. In a LDES, the conducting electrons are confined within the nanometer distance scale so that the electronic subband energy, the electron kinetic energy, the Fermi energy, etc. are on the meV scale (noting that $\omega\sim$THz for $\hbar\omega\sim$meV). Therefore, THz electromagnetic radiation may couple strongly to the device system. Furthermore, the results obtained from a recent theoretical study show[2] that for an $Al_xGa_{1-x}As/GaAs$-based LDES driven by THz electromagnetic fields, the inverse of the relaxation time (or scattering rate) caused by electron interactions with impurities and phonons is also on the scale of THz (i.e., $1/\tau\sim10^{12}$ s^{-1}), which implies that THz radiation may modify strongly the processes of the momentum and energy relaxation for the excited electrons in the device systems. Hence, THz techniques are of significant impact on the characterizations of condensed-matter materials, especially for low-dimensional semiconductor systems and semiconductor nanostructures.

With the development and application of state-of-the-art techniques such as free-electron lasers (FEL's), it has become realistic to investigate the electronic properties of a device under THz electromagnetic radiation. FEL's can provide the source of the linearly polarized intense THz radiation with which one can study the frequency-dependent physical properties through measuring, e.g., dc conductivity,[3–5] photon-assisted tunneling,[6] cyclotron resonance,[7] etc. For the application of LDES's as THz radiation detectors, it is essential to study absorption of the device of electromagnetic radiation. One of the most important and the most popularly used experimental techniques to study optical absorption is to measure the response of the dc conductivity (or resistivity) to the radiation fields. Recently, linear and nonlinear electron transport in THz-driven two-dimensional electron gases (2DEG's) at zero magnetic field has been studied experimentally,[3,4] where some important and interesting results were reported. At low temperatures and in the presence of quantizing magnetic fields, photon-modified Shubnikov–de Hass oscillations have been observed experimentally for a 2DES (Ref. 5) and the measurements of FIR cyclotron absorption in $Al_xGa_{1-x}As/GaAs$ heterojunctions have been carried out recently.[8]

In this paper, we present a detailed theoretical study of electron (magneto)transport in THz-driven 2DEG's in strong magnetic fields at relatively high temperatures. At high temperatures ($T>50$ K), electron interactions with optical phonons will play an important role in determining the electronic transport properties. Now we enter a regime with different competing energy scales: (i) electronic subband energy (ε_n); (ii) Fermi energy (or chemical potential μ^*); (iii) cyclotron energy ($\hbar\omega_c$); (iv) phonon energy ($\hbar\omega_Q$); (v) photon energy ($\hbar\omega$); (vi) thermal broadening (k_BT); and (vii) Landau-level broadening (Γ_N). For an $Al_xGa_{1-x}As/GaAs$-based 2DES driven by THz electromagnetic fields and by strong magnetic fields, all these energies (frequencies) are on the meV (THz) scale. This offers us a possibility to observe photon-induced quantum resonance effects. We will limit ourselves to a situation where the energy relaxation of electrons is mainly through the absorption of photons and the absorption and emission of longitudinal optical (LO) phonons. We are interested in the effects which are a consequence of electronic transitions among different Landau levels (LL's) via electron interactions with photons and with LO phonons. In such a case, we predict that when a condition $M\omega_c+\omega=\omega_{\rm LO}$ (where $\omega_{\rm LO}$ is the LO-phonon frequency and M is an index difference between two LL's) is satisfied, resonant scattering will occur between two LL's so that the dc resistivity and the optical absorption coefficient will be enhanced. Consequently, these quantities are expected to oscillate as a function of magnetic field and/or photon frequency. This resonance effect, we call it *magneto-photon-phonon resonance* (MPPR), is electrically analogous to the magnetophonon resonance (MPR) (Ref. 9) and electrophonon resonance (EPR) (Refs. 10 and 11) which are observed in the absence of the electromagnetic radiation.

In the present study, we develop a model, in Sec. II, which can be used to study magnetotransport in an electron-photon-phonon system in 2DEG structures. The results obtained for the observation of the magneto-photon-phonon resonance effect are presented and discussed in Sec. III. Our conclusions from this study are summarized in Sec. IV.

II. FREQUENCY-DEPENDENT MAGNETORESISTIVITY IN 2DEG'S

There exist a number of theoretical studies on the frequency-dependent magnetoconductivities (or resistivities) in 2DEG's.[12–14] However, most of the published work (e.g., in Refs. 12–14) is focused on the problem of cyclotron resonance, which is essentially a low-temperature effect and mainly caused by electron interactions with elastic scattering mechanisms (e.g., with impurities). In this paper, we consider a relatively high-temperature regime where electron interactions with LO phonons are the main processes for electron energy relaxation accompanied by optical absorption. Taking into account a configuration in which (i) the growth direction of a 2DES is along the z axis; (ii) the magnetic field is applied perpendicular to the interface of the 2DES [i.e., $\mathbf{B}=(0,0,B)$]; (iii) the electromagnetic radiations are polarized along the x direction; and (iv) the effect of the electromagnetic field with a frequency ω can be represented by an ac electrical field with a frequency ω, the frequency-dependent magnetoconductivities can be derived using, e.g., the Kubo formula in the linear response approximation. In this paper, we employ a simple model proposed by Ting *et al.*[12] to calculate the magnetotransport coefficients in the presence of THz electromagnetic fields and of electron–LO-phonon interactions. Following the derivation presented in Ref. 12, the frequency-dependent magnetoconductivity in a 2DEG is obtained in the form of the Drude formula,

$$\sigma_{\pm}(\omega)=\sigma_{xx}\mp i\sigma_{xy}=\frac{n_e e^2}{m^*(\omega)}\frac{\tau}{1-i(\omega\mp\omega_c^*)\tau}, \qquad (1)$$

where n_e is the electron density of the 2DEG, $m^*(\omega)=m^*[1+M_1(\omega)/\omega]$, $\tau=M_2^{-1}(\omega)m^*(\omega)/m^*$ and $\omega_c^*=\omega_c m^*/m^*(\omega)$ are, respectively, the frequency-dependent effective electron mass, relaxation time, and cyclotron frequency (with m^* the effective electron mass and $\omega_c=eB/m^*$ the cyclotron frequency in the absence of the ac field), and $M(\omega)=M_1(\omega)+iM_2(\omega)$ is the memory function induced by electron interactions with impurities, phonons, etc. The memory function for electron-impurity scattering has been documented in Refs. 12 and 15, and for electron-phonon scattering in Ref. 15. From Eq. (1), the longitudinal and transverse magnetoconductivity are given, respectively, by

$$\sigma_{xx}=\frac{n_e e}{B}\frac{\omega_c^*\tau(1-i\omega\tau)}{(1-i\omega\tau)^2+(\omega_c^*\tau)^2}$$

and

$$\sigma_{xy}=\frac{n_e e}{B}\frac{(\omega_c^*\tau)^2}{(1-i\omega\tau)^2+(\omega_c^*\tau)^2}. \qquad (2)$$

We find that in the presence of an ac driving field, it is more convenient to study the frequency-dependent magnetoresistivities which are given by

$$\rho_{xx}=\frac{B}{n_e e}\frac{1-i\omega\tau}{\omega_c^*\tau}$$

and

$$\rho_{xy}=\frac{B}{n_e e}. \qquad (3)$$

We note that in the presence of electromagnetic radiation, the real part of the transverse conductivity Reσ_{xy} (resistivity Reρ_{xy}) will deviate from (remain as) the conventional Hall effect.

To study the magneto-photon-phonon resonance, in the present paper we take into consideration electron interactions only with LO phonons. After (i) introducing the Hamiltonian for electron–LO-phonon interaction into the model proposed in Ref. 12, (ii) ignoring the effects of electron-electron interactions, and (iii) ignoring the contribution from photon emission, the memory function for electron–LO-phonon scattering is obtained in a simple form:

$$M(\omega)=-\frac{1}{m^*\omega n_e}(N_\omega-N_0)\sum_{\mathbf{Q}} q_x^2|u(Q)|^2\Pi(q,\omega_{\rm LO}-\omega), \qquad (4)$$

where $N_0=[e^{\hbar\omega_{\rm LO}/k_BT}-1]^{-1}$ and $N_\omega=[e^{\hbar(\omega_{\rm LO}-\omega)/k_BT}-1]^{-1}$, $\mathbf{Q}=(\mathbf{q},q_z)=(q_x,q_y,q_z)$ is the phonon wave vector, and $\Pi(q,\omega)=\Pi_1(q,\omega)+i\Pi_2(q,\omega)$ is the Fourier transformation of the electron density-density (d-d) correlation function. Further, applying the Fröhlich Hamiltonian to a 2DEG, the square of the electron–LO-phonon interaction matrix element is given by $|u(Q)|^2=4\pi\alpha L_0(\hbar\omega_{\rm LO})^2G(q_z)/Q^2$ with α the electron–LO-phonon coupling constant, $L_0=(\hbar/2m^*\omega_{\rm LO})^{1/2}$ the polaron radius, and $G(q_z)=|\langle 0|e^{iq_z z}|0\rangle|^2$ the form factor for electron-phonon interaction. Here we have considered a situation where only the lowest electronic subband is occupied by the electrons, which corresponds to a case when the electron density is less than 6×10^{15} m^{-2}.[16] Under some approximations, the memory function given by Eq. (4) for electron–LO-phonon interaction is found to be similar to those obtained by other authors in Ref. 15 (which is based on a momentum-balance equation approach) and Ref. 17 (which takes into account the full current-current correlations in the

Kubo formula). Equation (4) can be obtained from Eqs. (37) and (38) in Ref. 15 by taking (i) the linear response approximation, i.e., $T=T_e$; (ii) $[\pi(\omega_1+\omega-\omega_{\rm LO})]^{-1}\rightarrow\delta(\omega_1+\omega-\omega_{\rm LO})$; (iii) $\omega_0=\mathbf{q}\cdot\mathbf{v}\ll\omega$ with $\mathbf{v}$ the drift velocity of electrons; and (iv) the phonon relaxation time $\tau_{\rm ph}\rightarrow 0$. We note that (i) in this paper we have confined our study within the linear response regime due to the usage of the Kubo formula; (ii) the experimental measurements reported in Refs. 3 and 4 are carried out at strong ac driving fields ($E_{\rm ac}\sim$kV/cm) under a weak dc bias ($E_{\rm dc}<2$ V/cm) so that $\omega_0\ll\omega$ is a good approximation in the theoretical model dealing with the THz radiation frequencies. Furthermore, due to $E_{\rm ac}\gg E_{\rm dc}$, the effects of a dc bias cannot be seen in the linear response theory; and (iii) a very weak hot-phonon effect has been indicated by the experimental results reported in Ref. 3. We find that Eq. (4) can also be obtained from Eqs. (2.33) and (2.33′) in Ref. 17 by taking the phonon propagator to be a δ function and ignoring the effects of screening due to the self-consistent field.

It can be justified that under THz electromagnetic radiations $M_1(\omega)/\omega\ll 1$, which results in $m^*(\omega)\simeq m^*$, $\omega_c^*\simeq\omega_c$ and

$$\frac{1}{\tau}\simeq M_2(\omega)=-\frac{\alpha L_0(\hbar\omega_{\rm LO})^2}{2\pi m^*\omega n_e}(N_\omega-N_0)\times\int_0^\infty dq\, q^3X(q)\Pi_2(q,\omega_{\rm LO}-\omega), \tag{5}$$

where $X(q)=\int_{-\infty}^{\infty}dq_zG(q_z)/(q^2+q_z^2)$ and the imaginary part of the electron d-d correlation function in the presence of strong magnetic field and in the absence of electron-electron screening is given by[12,18]

$$\Pi_2(q,\omega)=-\frac{2}{\pi^2l^2}\sum_{N',N}C_{N',N}(l^2q^2/2)\times\int_{-\infty}^{\infty}dE[f(E)-f(E+\hbar\omega)]\times{\rm Im}G_N(E){\rm Im}G_{N'}(E+\hbar\omega). \tag{6}$$

Here, N is the index for the Nth LL, $l=(\hbar/eB)^{1/2}$ is the magnetic length, $f(E)=[e^{(E-\mu^*)/k_BT}+1]^{-1}$ is the Fermi-Dirac function, and $C_{N,N+J}(x)=[N!/(N+J)!]x^Je^{-x}[L_N^J(x)]^2$ with $L_N^J(x)$ the associated Laguerre polynomial. Further, ${\rm Im}G_N(E)$ is the imaginary part of the Green's function for the Nth LL. In principle, the imaginary and real parts of the Green's function for the LL's can be determined by, e.g., self-consistent calculations,[9,19] but this complicates the numerical calculation considerably and we do not attempt it in the present study. In this paper, we use a Gaussian type of LL shape which is a phenomenological LL structure and given by

$${\rm Im}G_N(E)=-\frac{\pi}{\sqrt{2\pi}\Gamma_N}e^{(E-E_N)^2/2\Gamma_N^2}, \tag{7}$$

with $E_N=(N+1/2)\hbar\omega_c$ the Nth LL energy and Γ_N the width of the Nth LL. For the LL broadening induced by short-range impurity scattering, $\Gamma_N^2=\Gamma^2=(2e\hbar/\pi\mu_0m^*)\hbar\omega_c$ with μ_0 the quantum mobility at zero magnetic field at low-temperature limit.[14] To determine the term $X(q)$, we need to know the sample structure of the 2DEG. In this paper we consider an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunction. We make the usual triangular well approximation to model the confining potential along the growth direction and use the corresponding variational wave function.[14] Thus, we have $X(q)=(\pi/8q)(8+9y+3y^2)/(1+y)^3$ where $y=q/b$ and $b=[(48\pi m^*e^2/\kappa\hbar^2)(N_{\rm depl}+11n_e/32)]^{1/3}$ defines the thickness of the triangular well with κ the dielectric constant and $N_{\rm depl}$ the depletion charge density. Now, we can proceed with numerical calculations for the frequency-dependent magnetoresistivity in $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunctions.

III. RESULTS AND DISCUSSIONS

The results of this section pertain to $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterojunctions. For a model calculation, we use typical sample parameters for a heterojunction: (i) the electron density of the 2DEG $n_e=2\times10^{15}$ m^{-2}; (ii) the sample mobility at $B=0$, $\omega=0$, and $T\rightarrow 0$ is $\mu_0=2$ m^2/V s (which is used to determine the LL width); and (iii) the depletion charge density $N_{\rm depl}=5\times10^{14}$ m^{-2}. The material parameters corresponding to GaAs are: the effective electron mass $m^*=0.0665m_e$ with m_e the rest electron mass; the static dielectric constant $\kappa=12.9$; the LO-phonon energy $\hbar\omega_{\rm LO}=36.6$ meV; and the electron–LO-phonon coupling constant $\alpha=0.068$. Further, the chemical potential μ^* is determined by the condition of electron number conservation.

From Eq. (3) we see that under the linear response approximation, the transverse resistivity ρ_{xy} represents the conventional Hall effect, i.e., ρ_{xy} depends very little on the electromagnetic radiations. Hence, we may pay attention only to the longitudinal resistivity ρ_{xx}. The real and imaginary parts of ρ_{xx} are given, respectively, by

$${\rm Re}\rho_{xx}=\frac{B}{n_ee}\frac{1}{\omega_c\tau}$$

and

$${\rm Im}\rho_{xx}=-\frac{m^*}{n_ee^2}\omega. \tag{8}$$

Here, we see that ${\rm Im}\rho_{xx}\sim\omega$ and is independent of the magnetic field. Therefore, the real part of ρ_{xx} is of interest in the measurements of magnetoresistivity and the optical absorption coefficient.

The real part of the longitudinal magnetoresistivity as a function of magnetic field (photon frequency) is show in Fig. 1 (Fig. 2) at a fixed temperature $T=120$ K for different radiation frequencies (magnetic fields). The effects of MPPR can be clearly seen by spotting ${\rm Re}\rho_{xx}$ as a function of B and/or ω, which indicates that the MPPR effects may be observed experimentally by measuring the dependence of the dc resistivity (or conductivity) and the optical absorption coefficient on the magnetic fields (radiation frequency) at a fixed photon frequency (magnetic field). The peaks of ${\rm Re}\rho_{xx}$ can be observed around the MPPR condition: $M\omega_c+\omega=\omega_{\rm LO}$ with $M=1,2,3,\ldots$ being an index difference between two LL's. This corresponds to electronic transitions between two LL's accompanied by the processes of

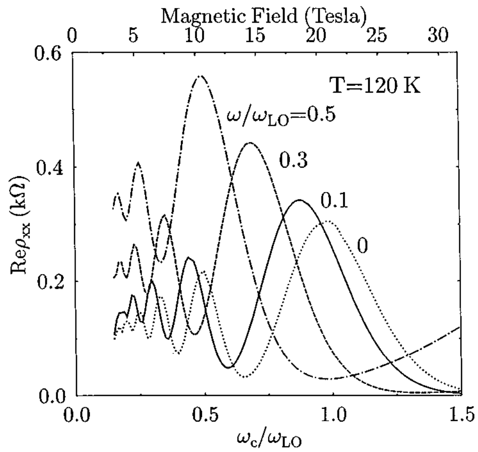

FIG. 1. Magneto-photon-phonon resonance observed by measuring dc resistivity as a function of magnetic field at a fixed temperature T for different radiation frequencies. $\omega_{LO}=55.6$ THz for GaAs.

photon absorption and LO-phonon emission. The results shown in Fig. 2 and obtained from our further calculations have indicated that by plotting Reρ_{xx} as a function of radiation frequency at a fixed magnetic field, a stronger MPPR oscillation can be observed around a magnetic field where ω_{LO}/ω_c is an integer number (see Fig. 2), i.e., when the condition of MPR is satisfied. This can be understood by the fact that (i) the density of states (DOS) for a 2DEG in strong perpendicular magnetic fields is a series of Gaussian-function (or δ-function, in an ideal case) peaks centered at each LL; (ii) in GaAs-based LDEG's, electrons interact much more strongly with phonons than with photons; and (iii) the strongest optical absorption occurs among different LL's when the condition of cyclotron resonance (CR) is satisfied, i.e., when $I\omega_c=\omega$ with $I=1,2,3,\ldots$ being an index difference between two LL's. Therefore, we predict that the MPPR effect may be observed under the conditions of MPR.

From Fig. 1, we see that with increasing radiation frequency, the MPPR peaks corresponding to $M=1,2,3$, etc.

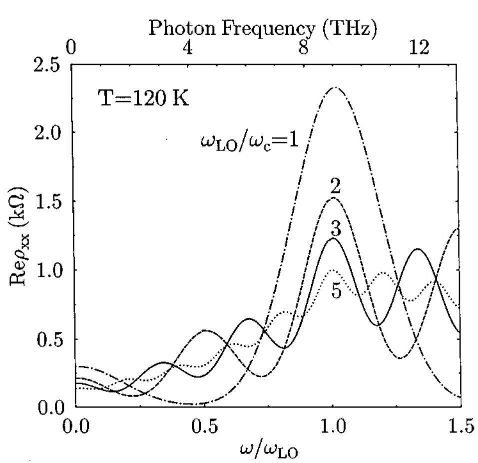

FIG. 2. Magneto-photon-phonon resonance observed by measuring dc resistivity as a function of radiation frequency for different magnetic fields. On the top, the photon frequency is shown by $f=\omega/2\pi$.

shift to the low-magnetic-field regime, which implies that the MPPR effect may be observed at relatively low magnetic fields. The physical reason behind this is that, in the presence of electromagnetic radiation, electrons can gain the energy from radiation fields to reach the higher LL's through optical absorption processes. This is the electrical equivalent of a reduction of the LO-phonon energy so that the resonance occurs at a lower B field, i.e., at the condition $M\omega_c=\omega_{LO}-\omega$. We note that by looking at the dependence of magnetoresistivity (or conductivity) and the optical absorption coefficient on the magnetic fields (i) the number of MPPR peaks decreases with increasing radiation frequency because M decreases with increasing ω; (ii) the MPPR oscillation cannot be observed at very high radiation frequencies (i.e., for $\omega>\omega_{LO}$) because the possibility of electronic transitions via resonant processes of photon-absorption and LO-phonon emission is suppressed; and (iii) the amplitude of the corresponding MPPR peaks observed in Reρ_{xx} increases with radiation frequency due to the effect of optical absorption. An important conclusion we draw from Fig. 1 is that a stronger resonant absorption of higher-frequency electromagnetic radiation may occur at a lower magnetic field under the MPPR condition.

The results presented in Fig. 2 show that (i) the strongest MPPR oscillation can be observed around $\omega=\omega_{LO}$ at high magnetic fields. In this situation, the energy transfer for electrons during the electronic transitions via photon-absorption and LO-phonon emission is very small; (ii) the amplitude of the MPPR peak at $\omega=\omega_{LO}$ increases with magnetic field, which implies an enhancement of the resonant-optical absorption by the magnetic fields; (iii) within a certain radiation frequency range, the number of MPPR peaks decreases with increasing magnetic field; (iv) the oscillations of Reρ_{xx} with ω can still be observed at low magnetic fields when $\omega>\omega_{LO}$. This is due to the effect of cyclotron absorption; and (v) the amplitude of oscillations decreases with magnetic field. The results obtained from the further calculations show that at very high magnetic fields (i.e., $\omega_c>\omega_{LO}$) the amplitude of the oscillation of Reρ_{xx} with ω, where a peak can be found at $\omega=\omega_{LO}$, deceases rapidly with increasing magnetic field.

In the present study, our numerical results are presented for a temperature $T=120$ K. In the absence of electromagnetic radiation, the results obtained from experimental measurements and theoretical calculations have indicated that the magnetophonon resonance effect can be observed for an $Al_xGa_{1-x}As$/GaAs-based 2DEG over a temperature regime $100<T<200$ K.[9] From the fact that in these sample systems at high temperatures the electron–LO-phonon interactions are much stronger than the electron-photon interactions, we may expect that the effect of MPPR can also be observed experimentally over the temperature range $100<T<200$ K. In our model, we have ignored the contribution from photon emission to the resistivity (or conductivity). This contribution is supposed to be much smaller than that from absorption in THz frequency regime, due to (i) a reduced effective phonon occupation number $n[\hbar(\omega_{LO}+\omega)/k_BT]$ with $n(x)=(e^x-1)^{-1}$ (note that for the case of optical absorption we have a term $n[\hbar(\omega_{LO}-\omega)/k_BT]$, see Eq. (4)) and (ii) a reduced electron d-d correlation function $\Pi(q,\omega_{LO}+\omega)$ [whereas for optical absorption we have a term

$\Pi(q,\omega_{\mathrm{LO}}-\omega)$ shown in Eq. (4)]. We did not include the effects of electron-electron (e-e) screening within our calculations. The theoretical results reported have shown that at relatively high temperatures (and/or high-electron temperatures) the influence of the e-e screening on the transport properties (e.g., electron mobility,[10,20] magnetoresistivities,[9] and electron energy loss[21]) is rather weak. This is because the inclusion of e-e screening through, e.g., random phase approximation results in an enhancement of the effective rate of electron scattering due to dynamical effects and in a reduction of the density of states by static screening over the entire temperature and electron density region. The compensation of these two processes suppresses greatly the effect of e-e screening on the transport properties. Further, we have used a phenomenological LL shape in our calculations and we have used the result obtained from short-range scattering for the LL width, to avoid a heavy numerical calculation in determining the LL structure through, e.g., the self-consistent calculations.[9,19] From our study of magnetophonon resonance,[9] we know that a fully self-consistent determination of the LL structure could improve the theoretical results significantly in reproducing the experimental findings. We did not attempt it in the present study, mainly because no experimental measurement has been reported so far on the MPPR effects, to the best of our knowledge.

IV. SUMMARY

In this paper, we have studied the effect of magneto-photon-phonon resonance observed in two-dimensional semiconductor systems in the presence of strong magnetic fields and terahertz electromagnetic radiation. This effect is a consequence of electronic transitions among different Landau levels accompanied by the processes of optical absorption and LO-phonon emission, and is electrically analogous to the magnetophonon resonance and electrophonon resonance. We have developed a simple theoretical model to study the high-field magnetotransport in THz-driven 2DEG's and the optical absorption. The main results obtained from this study are summarized as follows.

The magnetotransport in THz-driven 2DEG's and/or the optical absorption in strong magnetic fields can be investigated by looking into the frequency-dependent magnetoresistivities which can be directly applied to the calculation of the frequency-dependent conductivity and of the optical absorption coefficient. At relatively high temperatures, where electron–LO-phonon interactions are of the most importance in the electron scattering mechanisms, we find that (i) the transverse resistivity ρ_{xy} remains with the conventional Hall effect, whereas the conductivity σ_{xy} will deviate from the Hall effect and will depend on the radiation frequency; (ii) the imaginary part of the longitudinal resistivity $\mathrm{Im}\rho_{xx}\sim\omega$ and is constant in magnetic field; and (iii) only $\mathrm{Re}\rho_{xx}$ is of interest in studying frequency-dependent magnetoresistivities.

We have studied the dependence of $\mathrm{Re}\rho_{xx}$ on the magnetic field and on the radiation frequency. The results indicate that (i) the effect of magneto-photon-phonon resonance can be observed through measuring, e.g., the dc resistivity or conductivity as a function of magnetic field (photon frequency) at a fixed radiation frequency (magnetic field); (ii) $\mathrm{Re}\rho_{xx}$ oscillates with B and/or with ω, and the peaks of MPPR can be observed when the condition $M\omega_c+\omega=\omega_{\mathrm{LO}}$ is satisfied; (iii) by plotting $\mathrm{Re}\rho_{xx}$ as a function ω, a stronger MPPR occurs around magnetic fields at which the conditions of magnetophonon resonance is satisfied; (iv) the strongest oscillation observed by plotting $\mathrm{Re}\rho_{xx}$ versus ω appears at $\omega\simeq\omega_{\mathrm{LO}}$ and the amplitude of the peak increases with magnetic field. It suggests a magnetic-field-enhanced optical absorption effect; (v) with increasing magnetic field, the corresponding MPPR peaks observed by plotting $\mathrm{Re}\rho_{xx}$ versus B shift to the low-magnetic-field regime, which implies that the MPPR effect may be measured at relatively low magnetic fields in comparison with the observation of magnetophonon resonance; (vi) when $\omega>\omega_{\mathrm{LO}}$, the MPPR oscillations can not be seen by varying magnetic field whereas $\mathrm{Re}\rho_{xx}$ still oscillates with ω at low magnetic fields; and (vii) at MPPR conditions, the amplitude of the peaks shown in $\mathrm{Re}\rho_{xx}$ increases with radiation frequency. Together with those stated in (v) and shown in Fig. 1, we may suggest that a stronger absorption of the higher-frequency radiation will occur at lower magnetic fields.

The theoretical results presented and discussed in this paper have indicated that high-field magnetotransport in THz-driven 2DEG's is very rich both in physics and in device applications. From the fundamental study point of view, THz electromagnetic radiation brings us a possibility to observe photon-induced novel quantum resonance effects through simple and classic measurements such as transport measurements. And from the device application point of view, on the other hand, the investigation of electron (magneto)transport in THz-driven electronic systems would be very beneficial to the design and application of novel electronic, photonic and optoelectronic devices. For example, the magneto-photon-phonon resonance effect may be applied in frequency tunable far-infrared detectors and in the determination of the frequency of THz electromagnetic radiation.

ACKNOWLEDGMENT

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[1] See, e.g., M. J. Kelly, Mat. Sci. Eng. B **35**, 1 (1996).
[2] W. Xu and C. Zhang, Appl. Phys. Lett. **68**, 3305 (1996).
[3] N. G. Asmar, A. G. Markelz, E. G. Gwinn, J. C̃erne, M. S. Sherwin, K. L. Campman, P. E. Hopkins, and A. C. Gossard, Phys. Rev. B **51**, 18 041 (1995).
[4] N. G. Asmar, J. C̃erne, A. G. Markelz, E. G. Gwinn, M. S. Sherwin, K. L. Campman, and A. C. Gossard, Appl. Phys. Lett. **68**, 829 (1996).
[5] R. A. Mena, S. E. Schacham, E. J. Haugland, S. A. Alterovitz, P. G. Young, S. B. Bibyk, and S. A. Ringel, J. Appl. Phys. **78**, 6626 (1995).
[6] H. Drexler, J. S. Scott, S. J. Allen, K. L. Campman, and A. C.

Gossard, Appl. Phys. Lett. **67**, 2816 (1995); C. J. G. M. Langerak, B. N. Murdin, B. E. Cole, J. M. Chamberlain, M. Henini, M. Pate, and G. Hill, *ibid.* **67**, 3453 (1995).
[7] For a recent work see, e.g., N. N. Zinov'ev and L. J. Challis, Phys. Rev. B **49**, 14 466 (1994), and references therein.
[8] See, e.g., Y. Zhao, D. C. Tsui, M. B. Santos, M. Shayegan, R. A. Ghanbari, D. A. Antoniadis, and H. I. Smith, Phys. Rev. B **51**, 13 174 (1995), and references therein.
[9] See, e.g., D. R. Leadley, R. J. Nicholas, J. Singleton, W. Xu, F. M. Peeters, J. T. Devreese, J. A. A. J. Perenboom, L. van Bockstal, F. Herlach, J. J. Harris, and C. T. Foxon, Phys. Rev. Lett. **73**, 589 (1994); W. Xu, F. M. Peeters, J. T. Devreese, D. R. Leadley, and R. J. Nicoolas, Int. J. Mod. Phys. B **10**, 169 (1996), and references therein.
[10] W. Xu, F. M. Peeters, and J. T. Devreese, Phys. Rev. B **48**, 1562 (1993); J. Phys. Condens. Matter **5**, 2307 (1993).
[11] V. L. Gurevich, V. B. Pevzner, and G. Iafrate, Phys. Rev. Lett. **75**, 1352 (1995), and references therein.
[12] C. S. Ting, S. C. Ying, and J. J. Quinn, Phys. Rev. B **16**, 5394 (1977).
[13] For the recent theoretical studies see, e.g., A. P. Smith, A. H. MacDonald, and G. Gumbs, Phys. Rev. B **45**, 8829 (1992); E. Zaremba, *ibid.* **44**, 1379 (1991).
[14] For an early review see, T. Ando. A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1982).
[15] X. L. Lei and N. J. M. Horing, Phys. Rev. B **36**, 4238 (1987).
[16] R. Fletcher, E. Zaremba, M. D'Iorio, C. T. Foxon, and J. J. Harris, Phys. Rev. B **41**, 10 649 (1990).
[17] N. Tzoar and Chao Zhang, Phys. Rev. B **35**, 7596 (1987).
[18] W. Cai, X. L. Lei, and C. S. Ting, Phys. Rev. B **31**, 4070 (1985).
[19] See, e.g., W. Xu and P. Vasilopoulos, Phys. Rev. B **51**, 1694 (1995); W. Xu, P. Vasilopoulos, M. P. Das, and F. M. Peeters, J. Phys. Condens. Matter **7**, 4419 (1995).
[20] X. L. Lei, J. Phys. C **30**, 8 (1994).
[21] W. Xu, Phys. Rev. B **51**, 13 294 (1995).