Terahertz time-domain magnetospectroscopy of a high-mobility two-dimensional electron gas

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We have observed cyclotron resonance in a high-mobility GaAs/AlGaAs two-dimensional electron gas by using the techniques of terahertz time-domain spectroscopy combined with magnetic fields. From this, we calculate the real and imaginary parts of the diagonal elements of the magnetoconductivity tensor, which in turn allows us to extract the concentration, effective mass, and scattering time of the electrons in the sample. We demonstrate the utility of ultrafast terahertz spectroscopy, which can recover the true linewidth of cyclotron resonance in a high-mobility ($>10^6$ cm^2 V^{-1} s^{-1}) sample without being affected by the saturation effect. © 2007 Optical Society of America

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Quantum coherence is an important ingredient in modern condensed-matter physics as well as in emerging technologies. The creation and manipulation of a coherent superposition of multiple quantum states is the subject of many current studies. A high-mobility two-dimensional electron gas (2DEG) offers an ideal system for studying novel quantum coherent effects in a clean, solid-state environment. In particular, when one applies a magnetic field perpendicular to the 2DEG, the density of states splits into Landau levels, making a fully tunable, atomiclike system. In addition, a variety of phenomena that occur in the 2DEG due to carrier interactions, confinement, and disorder make coherent effects more exotic than in atomic or molecular systems. However, there has been little success in performing coherent spectroscopy of Landau-quantized 2DEGs, although there is a long history of cyclotron resonance (CR) studies of 2DEGs using Fourier-transform infrared (FTIR) spectroscopy [1–6].

Terahertz (THz) time-domain (TD) magnetospectroscopy [7], which combines THz TD spectroscopy (THz-TDS) with a high magnetic field, has a number of inherent advantages over traditional FTIR techniques. THz-TDS directly measures the amplitude and phase of the electric field $E(t)$ and allows the simultaneous determination of the real and imaginary parts of the conductivity without using Kramers–Kronig techniques. Additionally, use of a temporally gated detection scheme, common to THz-TDS techniques, significantly suppresses background thermal noise and results in an enhanced signal-to-noise ratio [8,9].

THz-TDS was used earlier [10] to observe CR in relatively low-mobility ($\mu_e = 2.7 \times 10^5$ cm^2 V^{-1} s^{-1}) 2DEG samples. In addition, THz-TDS has been successfully employed to study quantum coherent phenomena in a wide range of systems, including the rotational transitions of N_2O molecules [11], intersubband transitions in semiconductor quantum wells [12], and surface plasmons propagating on metal-film hole arrays [13].

Here, we report the observation of long-lived, magnetic-field-dependent coherent oscillations in a *high-mobility* GaAs/AlGaAs 2DEG in a perpendicular magnetic field. We explain our observations in terms of a coherent superposition created by the incident THz pulse between the lowest unfilled Landau level and the highest filled Landau level. In addition, we determine elements of the complex magnetoconductivity tensor $\tilde{\sigma}$ as a function of both frequency ν and magnetic field B, which, in turn, allows us to determine the cyclotron frequency ν_c, effective mass m^*, and cyclotron resonance linewidth $\Delta\nu_c$ (or the scattering time $\tau = 1/\Delta\nu_c$) as a function of B. Finally, we show that THz-TDS can overcome the "saturation effect" [14,15] that often prevents FTIR-based techniques from determining the true linewidths of CR in high-mobility ($\mu_e > 10^6$ cm^2 V^{-1} s^{-1}) 2DEGs.

Broadband, ultrashort THz pulses were generated and detected by using a standard photoconductive antenna-receiver setup [8,9]. We used an Oxford superconducting magnet (SM-4000-10T) to produce fields ranging from 0 to 1.4 T and temperatures from 1.5 to 300 K. The sample studied was a modulation-doped GaAs/AlGaAs single quantum well with an electron concentration of $n_e = 2.0 \times 10^{11}$ cm^{-2} and mobility of $\mu_e = 3.7 \times 10^6$ cm^2 V^{-1} s^{-1} at 4.2 K, determined through Shubnikov–de Haas and dc conductivity measurements.

In this experiment, the THz waveform is measured after transmission through the sample in a B field from 0 to 1.4 T. Figure 1 plots these waveforms at 0 T [trace (a)] and 1.28 T [trace (b)]. Trace (c) is the difference between the transmitted THz electric field at 1.28 and 0 T highlighting the change to the THz transmission due to the B field (data enlarged ten times), which shows the B-induced oscillations of the THz electric field. We verify that the observed oscillations originate from the 2DEG and not a B dependence of any of the optics in the experiment by first measuring the B-dependent THz transmission in the absence of the 2DEG in an otherwise identical con-

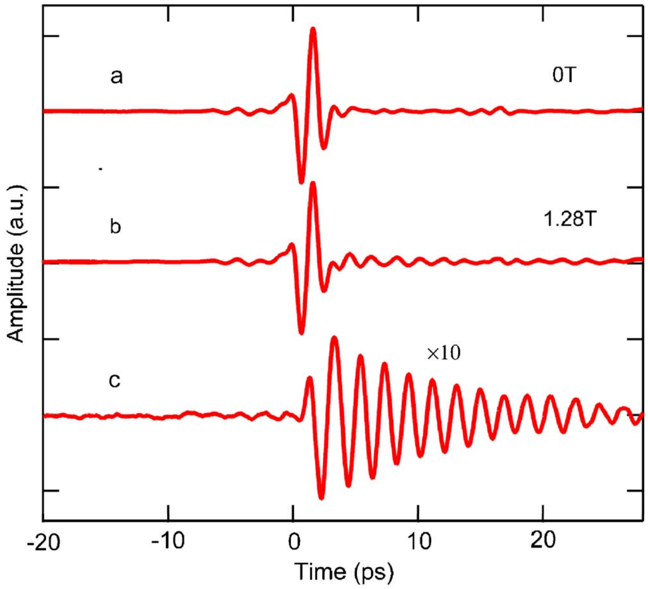

Fig. 1. (Color online) THz waveforms transmitted through a high-mobility 2DEG at (a) 0 T and at (b) 1.28 T at 2 K. The cyclotron oscillations induced by the magnetic field (c) are isolated by subtracting (a) from (b).

figuration. Figure 2(a) shows similar oscillations induced in the transmitted THz waveform from 0.7 to 1.4 T whose frequency and decay time vary with B.

Figure 3(a) shows the amplitude of the Fourier-transformed electric fields at 0 and 1.28 T. A B-field-induced absorption dip is clearly seen in the 1.28 T data. Figure 3(b) shows the magnitude of the complex transmission coefficient ($T=|T|e^{i\phi}$) at 1.28 T, while Fig. 3(c) shows the phase, ϕ. The THz pulse was linearly polarized ($\hat{x}$), and we detected only one polarization component ($\hat{x}$) after transmission through the sample. As a result, our measurement was dependent on the corresponding diagonal element of the magnetoconductivity tensor, σ_{xx} [1]. To extract the conductivity from the complex transmission coefficient, we model this sample as a thin conducting sheet on a thick substrate with a refractive index, n. In this approximation, the ratio of the Fourier transform of the waveform at a finite B field, $E(\nu,B)$, to the zero-field waveform, $E(\nu,0)$, is given by

$$T_{xx}(\nu,B)=\frac{E(\nu,B)}{E(\nu,0)}=\frac{2Y}{2Y+\sigma_{xx}(\nu,B)}, \qquad (1)$$

where $Y=n/Z_0$ is the admittance of the GaAs substrate and $Z_0=377\ \Omega$ is the impedance of free space [8]. Figure 3(d) highlights real (σ'_{xx}) and imaginary (σ''_{xx}) parts of the extracted conductivity tensor element at 1.28 T. Due to the rotational symmetry of the system perpendicular to the plane of the 2DEG, we would expect the same result in the case of input polarization and detection both along $\hat{y}$, i.e., $\sigma_{xx}=\sigma_{yy}$ [1].

We determine the cyclotron frequency ν_c (s^{-1}), the cyclotron resonance linewidth $\Delta\nu_c=1/\tau$ (s^{-1}), and the magnitude of the conductivity σ_0 (Ω^{-1}) by fitting the results shown in Figs. 3(c) and 3(d). Both the real (σ'_{xx}) and imaginary (σ''_{xx}) parts of the magnetoconductivity tensor element are fitted by

$$\sigma_{xx}=\sigma'_{xx}+i\sigma''_{xx}=\frac{\sigma_0}{1+2\pi i(\nu-\nu_c)\tau}. \qquad (2)$$

A representative fit at 1.28 T is shown in Fig. 3(d), using $\sigma_0=0.0126\ \Omega^{-1}$, $\nu_c=0.529$ THz, and $\tau=15.6$ ps.

An applied B field perpendicular to the 2DEG results in the formation of discrete Landau levels [see Fig. 2(b)] with an energy separation, ΔE, between the $|N\rangle$ and $|N+1\rangle$ levels given by

$$\Delta E=\hbar\frac{eB}{m^*}=h\nu_c, \qquad (3)$$

where e is the electron charge and h is the Planck constant. An incident THz wave with a photon energy equal to this separation coherently creates a superposition state between the highest filled Landau level, $|N\rangle$, and the lowest unfilled Landau level, $|N+1\rangle$, as shown in Fig. 2(b). This results in an atomiclike two-level system; all other Landau levels are either completely filled or completely empty (as long as the THz field is sufficiently weak as in our experiment) and do not affect the transmission of the THz pulse. The observed damped oscillations in our experimental data can thus be viewed as the free induction decay [16] of such coherently coupled Landau levels.

Using the extracted value of ν_c and Eq. (3), we obtain an effective mass of $0.0676m_0$, where m_0 is the free-electron mass. Also, using the extracted values of σ_0 and τ, we can determine the electron concentration to be $1.95\times10^{11}\ \mathrm{cm}^{-2}$, which is consistent with the concentration obtained from transport measurements ($2.0\times10^{11}\ \mathrm{cm}^{-2}$). Finally, the extracted linewidth is a measure of the scattering mechanisms present in the sample at this temperature and B field. We have systematically studied the temperature and B dependence of $\Delta\nu_c$, which would allow us to elucidate a detailed theoretical understanding of the physical origins of this linewidth.

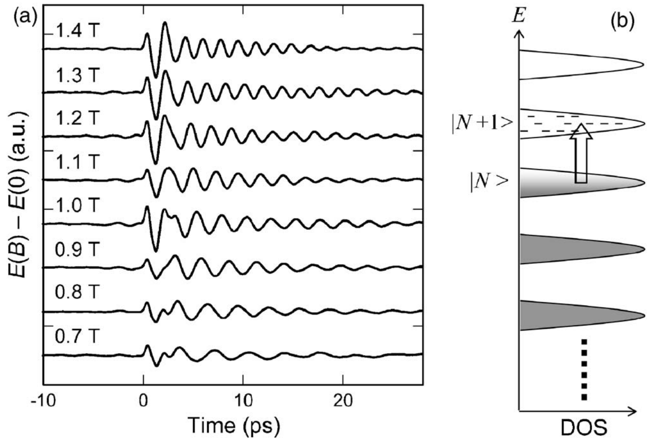

Fig. 2. (a) TD cyclotron oscillations in a high-mobility 2DEG from 0.7 to 1.4 T at 2 K. Traces are vertically offset for clarity. (b) Landau-quantized 2DEG.

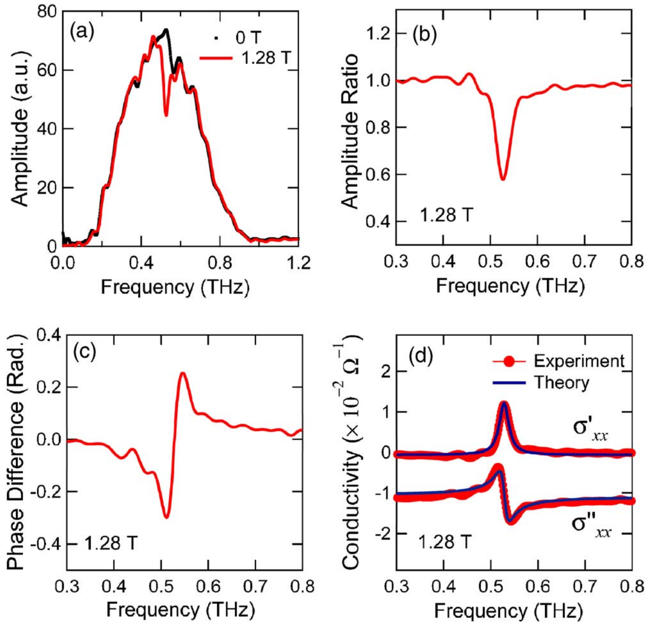

Fig. 3. (Color online) (a) Amplitude of the transformed electric fields at 0 and 1.28 T. (b) Magnitude of the complex transmission coefficient at 1.28 T. (c) Phase of the transmission coefficient. (d) Real (σ'_{xx}) and imaginary (σ''_{xx}) parts of the magnetoconductivity tensor element σ_{xx} at 1.28 T. The σ''_{xx} trace is vertically offset.

In high-mobility 2DEGs, the apparent linewidth measured by FTIR is larger than the true linewidth, a phenomenon commonly referred to as the "saturation effect" [14,15]. This results from the decrease in *detectable* transmission of THz radiation over a broad spectral range; as the conductivity increases with either increasing n_e or μ_e, a spectral region exists where, effectively, no transmission is permitted. The lack of a phase sensitive detection scheme in traditional FTIR techniques makes the direct determination of the complex conductivity in this situation difficult. Because of this saturation effect, almost no systematic linewidth studies exist for high-mobility 2DEGs ($>10^6\ \mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$).

To overcome the lack of phase sensitive detection in FTIR measurements, different methods have been proposed. For example, measurement of the transmission coefficient of a 2DEG over a broad spectral range will permit the use of Kramers–Kronig techniques to calculate the phase at THz frequencies and determine the complex conductivity. A second alternate method for determining the complex conductivity *assumes* a Drude form for $\tilde{\sigma}$ and fits this to the measured intensity transmission coefficient; lack of a direct phase measurement makes this an ambiguous determination of n_e and τ [14].

THz-TDS allows for the *direct* determination of the complex conductivity without resort to Kramers–Kronig analysis and without an *a priori* assumption of the lineshape function. The increased signal-to-noise ratio inherent to the gated detection scheme enables the detection of the lower transmitted THz signals that result from high-μ_e and high-n_e 2DEGs. Second, the additional spectroscopic information determined from the phase sensitive measurement removes the ambiguity between n_e and τ. As a result, no assumption of lineshape is necessary to calculate the complex conductivity. Employing this technique allows the simultaneous determination of both n_e and τ from the measurement of the transmitted THz waveform electric field.

In summary, we have observed TD cyclotron oscillations in a Landau-quantized 2DEG and determined the real and imaginary parts of the magnetoconductivity at different magnetic fields. We show that our THz technique has many advantages for doing cyclotron resonance measurements, especially for high-mobility samples.

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