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Terahertz cyclotron resonance spectroscopy of an AlGaN/GaN heterostructure using a high-field pulsed magnet and an asynchronous optical sampling technique

B. F. Spencer,1,a) W. F. Smith,1 M. T. Hibberd,1 P. Dawson,1 M. Beck,2 A. Bartels,2 I. Guiney,3 C. J. Humphreys,3 and D. M. Graham1
1School of Physics and Astronomy and the Photon Science Institute, The University of Manchester, Manchester M13 9PL, United Kingdom
2Laser Quantum GmbH, Max-Stromeyer-Str. 116, 78467 Konstanz, Germany
3Department of Materials Science and Metallurgy, 27 Charles Babbage Road, University of Cambridge, Cambridge CB3 0FS, United Kingdom

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The effective mass, sheet carrier concentration, and mobility of electrons within a two-dimensional electron gas in an AlGaN/GaN heterostructure were determined using a laboratory-based terahertz cyclotron resonance spectrometer. The ability to perform terahertz cyclotron resonance spectroscopy with magnetic fields of up to 31 T was enabled by combining a high-field pulsed magnet with a modified asynchronous optical sampling terahertz detection scheme. This scheme allowed around 100 transmitted terahertz waveforms to be recorded over the 14 ms magnetic field pulse duration. The sheet density and mobility were measured to be $8.0 \times 10^{12} \text{cm}^{-2}$ and $9000 \text{cm}^{2} \text{V}^{-1} \text{s}^{-1}$ at 77 K. The in-plane electron effective mass at the band edge was determined to be $0.228 \pm 0.002m_0$. 
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High electron mobility transistors (HEMTs) based on the GaN materials system are of great interest for applications in the field of power electronics due to their combination of high electric breakdown field and high electron mobility.1 The characterization of the two-dimensional electron gas (2DEG) formed at the GaN/AlGaN interface in HEMT structures, caused by the large differences in piezoelectric and spontaneous polarizations, has already revealed an advantageous high electron mobility and large sheet carrier concentration in the GaN channel.2 To optimize the performance of such structures requires knowledge of the electron effective mass within the 2DEG, a fundamental parameter in determining electronic transport. There is, however, considerable variation in the literature for the electron effective mass in AlGaN/GaN heterostructures with low temperature magneto-transport measurements giving values ranging from $0.185m_0$3 to $0.24m_0$.4

Cyclotron resonance (CR) spectroscopy is now a well-established technique for characterizing semiconductor materials and is the only noncontact technique able to provide a direct measurement of the electron effective mass. It has been used to provide a wealth of information on the properties of 2DEGs in AlGaaS/GaAs HEMT structures, enabling both device optimization5 and the study of fundamental physical phenomena.6 However, the precise measurement of the larger electron effective mass in GaN requires large magnetic fields which are typically only available at national-scale facilities.7,8

Recently, compact pulsed magnets have been developed, which can provide the high magnetic fields (up to 30 T) that were previously only accessible at national-scale facilities on a table-top in a laboratory environment.9 There have also been several reports of cyclotron resonance spectrometers being developed that combine pulsed magnetic fields with broadband laser-based terahertz radiation sources.10–12 Laser-based terahertz spectroscopy is a time-domain technique that typically employs slow scanning mechanical delay stages to acquire the terahertz waveforms through combining time-delayed near-infrared and terahertz pulses in a nonlinear medium or photoconductive antenna. The key challenge in utilizing these sources with pulsed magnetic fields has been in developing a detection scheme that can measure the terahertz waveforms within the several millisecond duration of the magnetic field. Approaches to achieving this have included both replacing the slow mechanical delay stage with a fast rotating mirror10 and using two lasers synchronized with an electronically controlled optical sampling (ECOPS) technique.12 The ECOPS scheme was the most suitable method for use with short duration magnetic field pulses as Noe II et al.12 showed that it could be used to record four terahertz waveforms during an approximately 14 ms magnetic field pulse.

In this letter, we report on the characterization of the 2DEG in an AlGaN/GaN heterostructure at a temperature of 77 K. The measurements were carried out using a laboratory-based cyclotron resonance spectrometer that incorporated a high-field pulsed magnet and an asynchronous optical sampling (ASOPS) terahertz detection scheme. The use of an ASOPS scheme allowed around 100 terahertz waveforms to be recorded over the approximately 14 ms magnetic field pulse. This enabled the determination of the effective mass, sheet density, and mobility for electrons in the 2DEG as $0.228 \pm 0.002m_0$, $8.0 \times 10^{12} \text{cm}^{-2}$, and $9000 \text{cm}^{2} \text{V}^{-1} \text{s}^{-1}$,

a)Electronic mail: Ben.Spencer@manchester.ac.uk
respectively. Prior to studying the AlGaN/GaN heterostructure, the capabilities of the spectrometer were determined using a high-mobility AlGaAs/GaAs heterostructure. The spectrometer was shown to be able to measure a 2DEG with a sheet density greater than $2.6 \times 10^{11}$ cm$^{-2}$ and a mobility of up to $1.8 \times 10^7$ cm$^2$ V$^{-1}$ s$^{-1}$.

The modulation-doped AlGaAs/GaAs heterostructure used to benchmark the spectrometer was grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate. It consisted of a 1.2 $\mu$m thick GaAs channel layer followed by a 60 nm thick undoped Al$_{0.34}$Ga$_{0.66}$As barrier layer, a silicon delta doping layer (2.5 $\times$ 10$^{12}$ cm$^{-2}$), a 200 nm thick undoped Al$_{0.33}$Ga$_{0.67}$As layer, and a 5 nm thick GaAs capping layer.

The AlGaN/GaN heterostructure comprised of a 2.4 $\mu$m thick unintentionally doped GaN channel region, a 1 nm AlN layer, a 26 nm thick Al$_{0.27}$Ga$_{0.73}$N barrier layer, and a 2 nm thick GaN cap grown by metal-organic chemical-vapor deposition on a 220 nm thick AlN nucleation layer on a c-plane sapphire substrate. The Al$_{0.27}$Ga$_{0.73}$N barrier layer was grown with a growth temperature of 1055°C and a V/III ratio of 1450 at a rate of 0.7 $\mu$m/h.

The pulsed magnet used was similar to that described elsewhere, but with an 8 mF capacitor bank that enabled the production of magnetic fields of up to 31 T. A sample temperature of 77 K was achieved inside the magnet bore by attaching the samples to the end of a sapphire tube (inner diameter 6 mm) that was connected to the cold finger of a continuous-flow cryostat (Microstat, Oxford Instruments). The ASOPS technique has previously been shown to enable nanosecond time delays to be achieved at kilohertz scan rates without the use of a mechanical delay stage. The commercial system employed here consisted of two mode-locked Ti:sapphire femtosecond lasers operating at repetition rates close to 1 GHz with a fixed frequency offset of 7 kHz (TL-1000-ASOPS and Taccor Power, Laser Quantum GmbH). An interdigitated photoconductive antenna (TeraSed, Laser Quantum GmbH) was used to generate broadband terahertz radiation pulses, and a 4 mm thick (110)-cut ZnTe crystal was used for detection in a cross-polarized electro-optic detection scheme.

The commercial ASOPS detection system was modified so that individual terahertz time-domain waveforms were recorded, and not averaged together over a period of several seconds as is normally the case. The offset frequency between the two lasers, $\Delta f_0$, of 7 kHz resulted in around 100 time-domain waveforms being recorded during the approximately 14 ms magnetic field pulse at $1/\Delta f_0$ intervals. Data were collected using a two-channel digitizer board (Razor Compuscope 1422, 200 MS/s, 1GS memory, Gage) that was capable of recording terahertz time-domain waveforms over a two second period. A schematic diagram of the spectrometer timing scheme is shown in Fig. 1. Synchronization was achieved using a single start trigger and electronic time delays for the magnetic field pulse (to initiate the discharge of the capacitor bank) and the voltage pulses applied to the photoconductive antenna for terahertz generation. Time delays 2 and 3 in Fig. 1 were adjusted to allow for the intrinsic time delay in the triggering of the digitizer board (delay 1), and to ensure the magnetic field pulse coincided with the second antenna bias voltage pulse, as monitored on an oscilloscope. Pulsing the bias allowed for larger voltages to be applied (up to 25 V), and larger terahertz electric fields generated, without exceeding the maximum power rating of the antenna. The magnetic field was measured using a two-turn pick-up coil located next to the sample and recorded on the second channel of the digitizer board. The terahertz waveforms measured during the magnetic field pulse (labelled 1, 2, and 3) each had a corresponding zero-field reference waveform (labelled R1, R2, and R3).

FIG. 1. A schematic diagram of the timing scheme employed to enable cyclotron resonance spectroscopy with a pulsed magnetic field and an asynchronous optical sampling terahertz detection technique. The terahertz waveforms measured during the magnetic field pulse (labelled 1, 2, and 3) each had a corresponding zero-field reference waveform (labelled R1, R2, R3, etc.). This was in order to remove the effect of any variation in the applied voltage over the duration of the bias pulse. The terahertz transmission spectra were calculated from the ratio of the power spectra acquired during the magnetic field pulse to their corresponding reference spectra. The power spectra were calculated from a fast Fourier transform of a 20 ps windowed region of the waveforms that were zero padded to $2^N$ data points. The windowing was used in order to remove the influence of etalon reflections in the sample while the zero-padding was used to increase the number of data points in the frequency domain.

Figure 2(a) shows the transmission of terahertz radiation through the AlGaAs/GaAs heterostructure during the application of a magnetic field pulse with a peak field of 3.19 T. The transmission was determined from the average of the terahertz waveforms acquired with 109 shots of the pulsed magnet. It should be noted, however, that the CR absorption features in the terahertz transmission could be observed with as little as 10 shots. The numerical aperture of the spectrometer (NA = 0.03) limited the transmission of terahertz radiation and determined both the number of shots required for a sufficient signal-to-noise ratio and the usable terahertz bandwidth. As can be seen from Fig. 2(a), an absorption feature was observed that tracked the temporal profile of the applied magnetic field pulse over the measurable terahertz
The terahertz radiation was linearly polarized along the x-axis, and we detected only this polarization component after transmission through the sample. Our measurement of the complex transmission function, $T_{xx}$, can therefore be related to the corresponding diagonal element of the magneto-conductivity tensor, $\sigma_{xx}$, using

$$T_{xx} = \frac{E_0(v)}{E_B(v)} = \frac{2Y}{2Y + \sigma_{xx}},$$

where $Y = \pi\hbar/Ze$ is the ratio of the refractive index of the surrounding material at THz frequencies to the free-space impedance $Z_0 = 377 \Omega$. Figures 2(b) and 2(c) show the real and imaginary parts of the diagonal element of the magneto-conductivity tensor for a magnetic field of 2.81 T. The oscillations seen in Figs. 2(b) and 2(c) are Fourier transform artifacts, which are caused by small artificial steps in the time-domain data. These steps are introduced by zero padding and cannot be completely suppressed by tapering the data down to zero at the window edges. The concentration and mobility of electrons within the 2DEG were determined from fitting the magneto-conductivity spectra with the Drude model. Fitting the spectra for all magnetic fields in this way (see supplementary material for further examples) gave an electron sheet concentration of $2.6 \times 10^{11} \text{cm}^{-2}$ and a scattering time of $\tau = 7.2 \text{ ps}$, which corresponds to a carrier mobility of $\mu = 1.8 \times 10^{8} \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, according to $\mu = e\tau/m^*$.

Van der Pauw measurements performed at both 2.4 K and 300 K gave an electron density of $2.2 \times 10^{11} \text{cm}^{-2}$ and $2.92 \times 10^{11} \text{cm}^{-2}$, and a mobility of $6.53 \times 10^6 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ and $6430 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, respectively. AlGaAs/GaAs heterostructures giving comparable 2.4 K and 300 K mobility values also have 77 K values in good agreement with those determined here by terahertz cyclotron resonance spectroscopy.

Figure 3(a) shows the terahertz transmission through an AlGaN/GaN heterostructure during the application of a magnetic field pulse with a peak field of 13 T. The results shown were calculated from the average of the terahertz waveforms acquired with 30 shots of the pulsed magnet. As can be seen, the CR absorption is broader than that observed in the AlGaAs/GaAs heterostructure, indicating a lower carrier mobility. Figure 3(b) shows the transmission calculated using the extracted 2DEG carrier parameters. The parameters were determined using the same fitting of magneto-conductivity spectra with the Drude model (see supplementary material) giving an electron sheet concentration of $8.0 \times 10^{11} \text{cm}^{-2}$ and a carrier scattering time of $1.4 \text{ ps}$, corresponding to a carrier mobility of $9000 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$.

The electron sheet concentration and mobility values are in good agreement with Hall measurements performed at 77 K on similar AlGaN/AlN/GaN heterostructures grown on sapphire. The electron effective mass was determined from plotting the terahertz transmission as a function of applied magnetic field, shown in Fig. 3(c). The frequency of the transmission minima extracted from Fig. 3(c) is shown in Fig. 3(d), from which an electron effective mass of $0.267 \pm 0.002 m_0$ was determined.

A temperature-dependent electron effective mass has been reported for an AlGaN/GaN HEMT structure, with a value varying from 0.22 to 0.36 $m_0$ at 1.5 K to 300 K, and accounted for by a variation of the electron wavefunction penetration into the AlGaN barrier layer. The inclusion of an AlN interfacial layer in the structure studied here, in addition to the low sample temperature employed, will prevent the wavefunction penetrating into the AlGaN barrier layer. The observed increase in the effective mass from the bulk-GaN value is instead considered to be a consequence of the large carrier concentration in the 2DEG. Using the modified two-band approximation for conduction band non-parabolicity employed by Syed et al. together with the simpler triangular potential approximation for the 2DEG confinement (see supplementary material), we determined that the non-parabolicity effect increased the measured electron effective mass by 17% for a sheet carrier concentration of $8.0 \times 10^{12} \text{cm}^{-2}$. Taking this non-parabolicity correction into account gave a band-edge effective mass of $0.228 \pm 0.002m_0$. 

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**FIG. 2.** (a) Terahertz transmission through an AlGaAs/GaAs heterostructure measured during the application of a pulsed magnetic field (with a maximum field of 3.19 T and a pulse duration of 4 ms FWHM). The inset shows the frequency of the transmission minima as a function of applied magnetic field, which enabled the electron effective mass to be determined according to Eq. (1). (b) Real and (c) imaginary components of the measured magneto-conductivity for a magnetic field of 2.81 T together with the results of fitting with the Drude model (red lines).
In summary, we have shown that by modifying an asynchronous optical sampling detection scheme cyclotron resonance spectroscopy may be performed with high-field pulsed magnets in a laboratory environment. In comparison to electronically controlled optical sampling methods, this scheme has enabled an order of magnitude increase in the number of terahertz waveform measurements that could be acquired during the magnetic field pulse. The development of this instrument has allowed us to determine the fundamental properties of a 2DEG in an AlGaN/GaN heterostructure. The band-edge effective mass, sheet electron concentration, and mobility at a sample temperature of 77 K were measured to be $0.228 \pm 0.002 m_0$, $8.0 \times 10^{12} \text{cm}^{-2}$, and $9000 \text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, respectively.

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FIG. 3. (a) Terahertz transmission through an AlGaN/GaN heterostructure measured during the application of a pulsed magnetic field with a maximum field of 13 T.  (b) Time-dependent terahertz transmission calculated using values of the 2DEG electron sheet concentration and mobility determined from fitting magneto-conductivity spectra with the Drude model. (c) Terahertz transmission plotted as a function of magnetic field from which the frequency of the transmission minima was determined. (d) CR absorption frequency as a function of applied magnetic field, used for extracting the electron effective mass according to Eq. (1) (red line).