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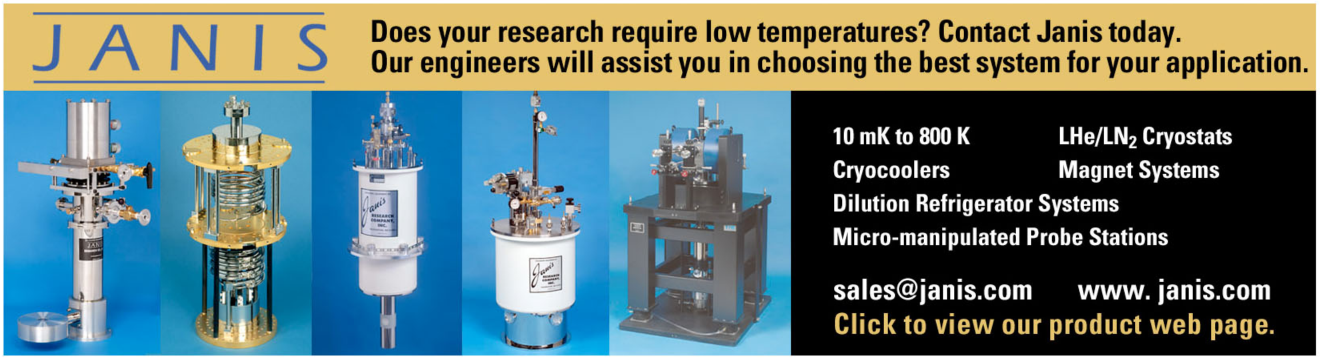

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Millimeter wave transmission spectroscopy of gated two-dimensional hole systems

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We developed a differential transmission to study cyclotron resonance of GaAs/Al$_x$Ga$_{1-x}$As two-dimensional hole samples. The technique utilizes a modulated AuPd gate isolated by a Si$_3$N$_4$ dielectric from the sample, which is irradiated opposite the gate by millimeter waves ranging from 2 to 40 GHz. This technique effectively removes the background signal and yields a hole effective mass of $0.41m_e$ with a cyclotron scattering time of ∼20 ps, consistent with the previous results using different techniques. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4711772]

Cyclotron resonance in two-dimensional (2D) systems has been studied extensively using a variety of techniques for high mobility 2D samples, ranging in wavelengths from gigahertz[1–4] to terahertz[5,6] such as transmission or absorption designs, which can yield the effective mass and the cyclotron scattering time.[7] The effective mass can also be determined from measuring the temperature-dependent amplitude of the Shubnikov-de Haas (SdH) oscillations[8,9] or through calorimetry measurements. However, previously there has not been a way to measure simultaneously and effectively both the magnetotransport and microwave transmission across a sample while being able to control the carrier density. Taking these requirements into account led us to develop a coaxial-based measurement probe and differential power transmission technique to measure the magnetic dependence on the millimeter wave transmission spectrum in all electrical measurements. This technique subtracts the large transmission background signal leaving only the signal from the 2D system, resulting in measurable cyclotron resonance peaks.[10] Since the measurement is done completely electrically, there is no need for optical transmission/absorption, enabling simultaneous transport measurements in the same cool down. Recent developments in the fabrication of C-doped (001) GaAs/AlGaAs 2D hole gas (2DHG) samples[4,11,12] have increased the mobility of the 2DHG substantially. Our measurements are motivated by the transport results reported by Yuan *et al.*[13]

Cyclotron resonance is achieved when the cyclotron frequency equals the frequency of irradiation, $\omega_c = eB/m^* = \omega_{MW} = 2\pi f$, where B is the magnetic field of the resonance, m^* is the effective mass, and f is the frequency of irradiation. This occurs when the transition energy $\hbar\omega_c$ between Landau levels (LL) N and $N+1$ matches the energy of ω_{MW} to make the transition to the next LL, $N+1$.[14] In the case of 2DHG samples, the effective mass of heavy holes is $m^* \approx 0.41m_e$,[2,15,16] and we expect the resonance to occur around ∼0.03–0.6 T for our frequency range 2–40 GHz.

Our measurement was performed with a top loading 3He system in a superconducting magnet. The probe we designed utilizes dual low loss coaxial lines to provide microwave power down to the sample, across a co-planar waveguide (CPW) geometry (inspired by the Engle Group[17]), and then back up to a microwave power detector at room temperature. The microwave source is an Agilent MG3694B function generator, which provides the sample with 2–40 GHz and a tunable power output of 0 → 100 mW. Attenuation at 20 GHz is approximately −33 dB from source to detector; a room temperature 8–40 GHz wide band power amplifier with approximately +30 dB is used to recover the signal. The sample is irradiated by a photolithographically defined AuPd CPW meander line antenna evaporated on a piece of undoped GaAs ⟨111⟩ (Figure 1(a)), which we also use to measure the transmission signal (Figure 1(b)). All the RF components are designed to be impedance matched to 50 Ω. We conjecture that it is the microstripe mode, using the gate as the ground plane (see Figure 1(a)), that is coupling to the 2DHG. The MW polarization was not taken into account in this experiment; however, future optimization through simulation of the transmission will increase understanding and sensitivity. By using a completely electronics-based measurement, we eliminate the complexity of using optical transmission/reflection, bolometer measurements, and we enable simultaneous transport and transmission measurements in a single cool down.

Our samples were an asymmetric 15 nm quantum well (QW) wafer and a 20 nm symmetric QW wafer (20 nm QW). The sample was prepared by polishing the back side to remove any metallic material ($\lesssim 50\,\mu$m of *Ga*) to allow millimeter wave coupling to the 2D hole gas. It was then etched to a photolithographically defined $1 \times 3\text{mm}^2$ Hall bar with wedged leads, and InZn was annealed to form the contacts to the 2DHG. Using a PECVD, a dielectric of Si$_3$N$_4$ (500 Å thick) was formed over the sample and windows were etched to expose the contacts using a reactive ion etcher. Last, a 1000 Å AuPd alloy gate (with a 50 Å adhesion layer of Ti) was evaporated over the Hall bar to control the carrier density. The alloy for the gate and the meander line was chosen for its lack of cyclotron resonance signal due to its small alloy scattering length and for its ability to retain electrical conductivity. Each finished sample was mounted on top of the meander line to irradiate the

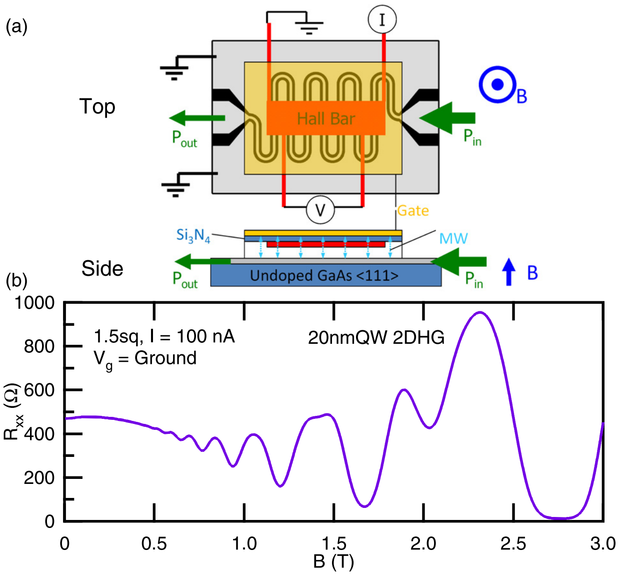

FIG. 1. (a) Microwaves were irradiated from the back side of the sample, while the sample's carrier density is controlled by the top gate, which acts as the ground plane for the CPW. (b) DC longitudinal resistance, SdH oscillations, of the 20 nm QW sample. Inset: geometry for simultaneous measurement of microwave transmission and gated magnetoresistance.

sample from the back side, and Au wires with In were used to make electrical connection. This geometry allowed us to measure the magnetoresistance and microwave power transmission in the same cool down while controlling the carrier density (Figure 1). The gated 15 nm QW and 20 nm QW samples had a carrier density of $2 \times 10^{11}\,\text{cm}^{-2}$ and $2.03 \times 10^{11}\,\text{cm}^{-2}$ with a mobility of $8 \times 10^5\,\text{cm}^2/\text{Vs}$ and $0.9 \times 10^5\,\text{cm}^2/\text{Vs}$, respectively. The large dimension of the Hall bar was used to increase the coupling with the microwaves. We focused on the 20 nm QW sample in this experiment.

To remove the background signal, we developed a single modulation differential power transmission measurement technique for the 2DHG sample. We accomplished this by irradiating the sample with monochromatic continuous wave microwaves (using the meander line) and by locking the microwave power sensor to the same modulation frequency as the gate. The gate modulates between V_g2, which depletes all of the carriers making up the background signal, and V_g1, which brings back the carriers. This was accomplished using a square wave at 17 Hz, the same frequency as the signal from the locked power sensor. V_g1 and V_g2 of the sample were identified by sweeping the gate voltage and calculating the hole carrier density, p. There is a slight hysteresis; however, it is negligible since V_g1 and V_g2 are chosen to be beyond the hysteresis range where the density saturates. For our sample, we chose $V_g2 = +2\text{V}$ to ensure that all free carriers were depleted from the system and $V_g1 = 0\text{V}$ to bring them back.

This technique led to a differential power output of ΔP, where $\Delta P = P_{out}(V_g1) - P_{out}(V_g2)$ from

$$P_{out}(V_g1) = P_{out}(V_g2) + \Delta P \times \left(\frac{1}{2} + \frac{2}{\pi}\left[\sum_n \frac{\sin((2n-1)x)}{2n-1}\right]\right), \qquad (1)$$

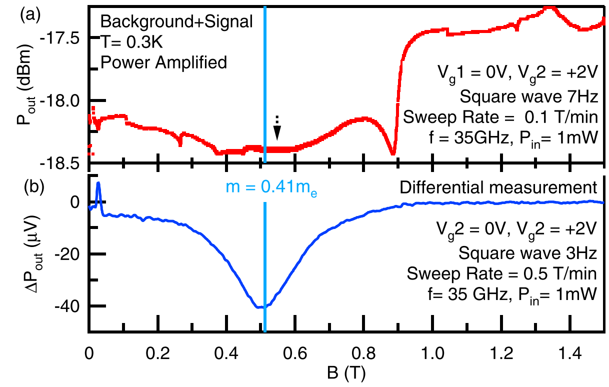

FIG. 2. Results from the modulating the gate voltage. (a) Calibrated transmitted power output signal. This signal includes both the background and the signal from the 2DHG that changes with the gate voltage. (b) The voltage output from the power sensor fed into a lock-in locked to the same frequency (17 Hz) as the gate modulation, which yields a strong peak that matches up closely with the cyclotron resonance associated with a hole effective mass of $\sim 0.41 m_e$.

which is represented as a square wave between V_g1 and V_g2. When taking the power amplifier into account, the sensitivity of this measurement technique is on the order of 100 pW (40 μV) from the results in Figure 2(b) with a modest input power of 1 mW, which results in a resolution around 0.1 ppm.

We verify that the output signal is linearly proportional to the input microwave signal in the range 0.01–3.17 mW. A Gaussian curve can be approximately fit to the differential transmission peaks, whose peak location, B_{min}, and full width half max, Γ, yielded the effective mass and cyclotron scattering time of $m^* = eB_{min}/2\pi f$ in terms of m_e, and $\tau_S = m^*/e\Gamma$, respectively.

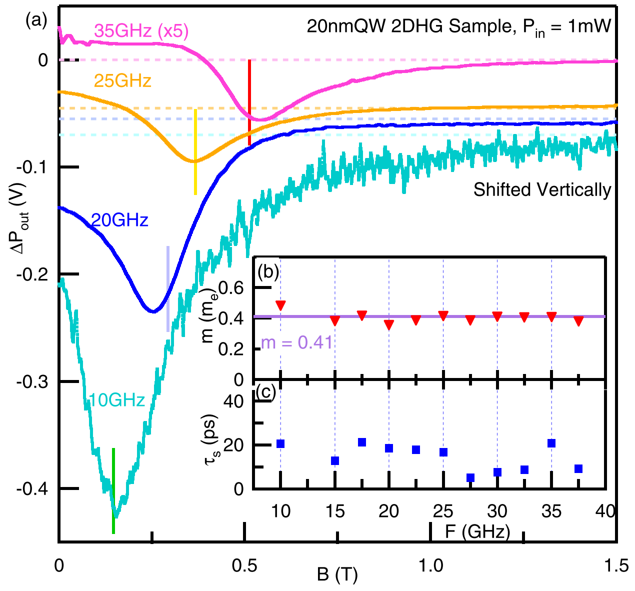

FIG. 3. (a) 20 nm QW 2DHG frequency dependence irradiated with $P_{in} = 1\text{mW}$, where the minima is visibly dependent on the frequency of irradiation, and the vertical lines are the expected cyclotron magnetic field using the known effective mass of $m = 0.41 m_e$. The MW transmission rate is frequency-dependent due to the circuit, which affects the signal amplitude and noise, especially near the limits of the amplifier. (b) Frequency-dependence of the effective mass with the known mass highlighted. (c) Frequency-dependence of the cyclotron scattering time.

In our frequency-dependence data from the 20 nm QW 2DHG sample (Figure 3), we note that the transmission minima is directly proportional to the irradiation frequency as we would expect from the cyclotron resonance, which also coincides with the higher frequency results from Cole *et al.*[18] This data allowed us to calculate the effective mass of the hole system to be $0.41m_e$, confirming the results from Kumar *et al.*[15] and Yuan, although they used different techniques. The values of the scattering time τ_s at some frequencies show large error bars because of weak signals.

These measurements show that the differential ΔP measurement technique we developed subtracts the background signal from that of the 2D system, leaving only the cyclotron resonance minimum in the transmission signal. From the preliminary data for this technique, we were able to identify the effective mass for the system, $0.41m_e$, confirmed by known values obtained from different techniques. We were also able to measure the cyclotron scattering time (∼20 ps). Spin splitting in the cyclotron resonance peak was not observed. This technique allows for the possibility to place a gated high mobility 2DHG sample in a two-axis magnet and look for the cyclotron spin splitting. The probe and ΔP technique developed from this experiment can be used to explore the microwave transmission of gated systems while simultaneously measuring electron/hole transport in the sample.

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