Remotely sensed in microwave irradiated GaAs/AlGaAs two-dimensional electron system

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Abstract. Remotely sensed microwave reflection was measured concurrently with standard magnetotransport in photo-excited high mobility GaAs/AlGaAs heterostructure. Experiments indicate strong reflection resonance on both sides of the magnetic field axis for linearly polarized microwave/terahertz photo-excitation over the examined frequency 30 < f < 330 GHz band. In addition, there is evidence for electronic heating in the vicinity of cyclotron resonance (CR), which is indicated by reduced amplitude of the Shubnikov-de Haas oscillations. Effective mass extracted from the measurements was found to equal the CR mass within experimental error.

1. Introduction
The discovery and study of microwave-induced zero-resistance states and associated magnetoresistance oscillations have brought new interest in the experimental-[1-22] and theoretical-[23-36] study of magnetotransport at high filling factors or low magnetic fields in the GaAs/AlGaAs 2D electron system.[1-36] Along with this interest in magnetotransport at high filling factors comes new concern for the microwave reflection, absorption, and transmission properties of the GaAs/AlGaAs 2DES at low magnetic fields, including the remote detection of the cyclotron resonance (CR), and the correlation of CR with magnetotransport. Thus, we developed a measurement technique that allows measuring the power signal of the microwaves reflected back from the photo-excited high mobility GaAs/AlGaAs device, while measuring standard magnetotransport, i.e., the diagonal resistance, $R_{xx}$, and the Hall resistance, $R_{xy}$, over wide frequency range from 30 to 330 GHz. From the observations and results, we identify CR and find the electron effective mass to equal CR mass.

2. Experimental
Experiments were conducted on two different samples of 200 µm-wide two dimensional GaAs/AlGaAs heterostructure Hall bars with gold-germanium contacts. For the first sample the carrier density $n \approx 2.4 \times 10^{11}$ cm$^{-2}$ and mobility $\mu \approx 10 \times 10^6$ cm$^2$/V s at temperature $T = 1.7$ K and for the second sample (data not shown in paper) $n \approx 3.3 \times 10^{12}$ cm$^{-2}$ and $\mu \approx 6 \times 10^6$ cm$^2$/V s at $T = 1.7$ K. Samples were mounted at the end of a long waveguide which was then inserted into a liquid helium cryostat with a superconducting solenoid as shown in Figure 1(a). During the experiments, the
magnetic field, $B$, was applied perpendicular to the 2DES and temperature was kept constant at 1.7 K. In the 30-50GHz band, linearly polarized microwaves were excited within the waveguide sample holder using an MW launcher coupled to a HP83650B MW source. A 6x-multiplier MM wave module provided radiation over the 65-110 GHz band, while 12x and 18x MW Virginia Diodes Multipliers generated microwave radiation from 140 to 330 GHz. Above 50 GHz, waveguides connected the source to the sample holder.

Standard four terminal low frequency (13 Hz) lock-in technique was used to collect the oscillatory magnetoresistive response, $R_{xx}$, of the high mobility GaAs/AlGaAs sample in sweeping $B$ and at constant microwave frequency, $f$. Additionally to recording $R_{xx}$, the microwave signal, reflected back from irradiated sample, was simultaneously collected using a power detector and read out with a power meter. As shown in Figure 1(a), a waveguide coupler on top of the waveguide holding the sample was used to direct the reflected microwaves to the detector. The microwave power at the source was $\sim 10^{-3}$ Watts up to 110 GHz, while the power of microwave signal reflected back from sample and collected with the power meter was $\sim 10^{-12}$ Watts.

![Figure 1](image)

Figure 1 (a) A schematic of the experimental setup showing long waveguide, with GaAs/AlGaAs sample at bottom end, in the liquid helium cryostat within a superconducting solenoid. Sample was irritated with microwaves (long solid line with arrow) and the microwave signal reflected back (long dotted line with arrow) was collected using a power detector on top of waveguide. (b) Diagonal resistance, $R_{xx}$ (right ordinate) and the reflected microwave power (left ordinate) as a function of magnetic field for samples of high mobility 2D GaAs/AlGaAs heterostructures at temperature $T = 1.7$ K and frequency $f = 267$ GHz.

3. Results and Discussion

Figure 1(b) shows the normalized reflected power signal (left ordinate) along with the diagonal resistance, $R_{xx}$, (right ordinate) as a function of magnetic field measured in a GaAs/AlGaAs 2DES with microwave excitation at 267 GHz. During measurements, linearly polarized microwaves were used, thus resonances on both sides, positive and negative magnetic field, is seen. In Figure 1(b), reflected power signal shows easily distinguishable resonance peaks. Though the peaks are not identical in shape, they do occur at same place on both side of the magnetic field axis, at $|B| = 0.66 \pm 0.02$ T. These strong disturbances in reflected power signal were observed over examined frequency band of 30 to 330 GHz.

Above $|B| = 0.3$ T, the diagonal resistance, $R_{xx}$ in Figure 1(b) shows regular Shubnikov-de Haas effect (SdH) with apparent reduction in the oscillations amplitude between $|B| = 0.60$ T and $|B| = 0.69$ T. In 2DES, temperature damping of SdH amplitude is a well-known, although not very precise,
method for locating cyclotron resonance (CR).[5] In the vicinity of CR, photo-excitation of electrons leads to the elevation of temperature or resonant electron heating. As SdH amplitude is particularly sensitive to heating, small increase in temperature near CR leads to the reduction of oscillations amplitude.[5,37] Thus, these strong resonance peaks in the reflected power signal and the resonant decrease in the SdH amplitude point to cyclotron resonance.

To better determine the physical origin of the resonance peaks in reflected power signal, their magnetic field positions were plotted as a function of the microwave frequency as shown in Figure 2. It is evident in Figure 2 that the resonance peak position in magnetic field, shown as filled circles, increase linearly with the MW frequency. Note here that each data point is an average over two peak locations in B, one at positive and one at negative B. The dashed line in Figure 2 is not a fit through the resonance positions, but a calculation of cyclotron frequency of electrons in an infinitely large GaAs/AlGaAs 2DES, that is \( f_C = eB/2\pi m^* \),[37] where the effective mass \( m^* = 0.067m_o \) (\( m_o \) is free electron mass). For the purpose of visual clarity, the linear fit through the data points is not shown in Figure 2, as it is almost indistinguishable from the dashed line shown. From the slope of linear fit (not shown), \( dB/df_{MW} = 0.00242 \pm 0.00007 \) T/GHz, we directly determined the effective mass ratio \( m^*/m_o = (0.0678 \pm 0.0020) \). For the second sample measured (data not shown), the effective mass ratio \( m^*/m_o = (0.0685 \pm 0.0022) \). Both mass ratios are within the experimental error of cyclotron effective mass, \( m^* = 0.067m_o \) for GaAs/AlGaAs devices. These results imply that the position of resonance peaks in reflected power signal coincide with the cyclotron resonance of electrons in a bulk 2DES. This is explained with the idea that when the sample undergoes cyclotron resonance, there will be enhanced MW absorption by the sample. As a consequence, there will be a change in the reflected power, which will be the signature of CR.

![Figure 2](image-url)

**Figure 2** Filled circles show the location of resonance peaks in the reflected power signal in magnetic field as a function of incident microwave frequency, \( f_{MW} \). Dashed line is not a fit through the data, and instead demonstrates the cyclotron frequency of electrons, \( f_C = eB/2\pi m^* \), where the effective mass \( m^* = 0.067m_o \).

4. Conclusions

We investigated microwave reflection in high mobility GaAs/AlGaAs over wide range of microwave frequencies. We found that the reflected power signal displays easily distinguishable resonance peaks that point to the cyclotron resonance. Since the radiation frequency, \( f \), was well known in the experiment, and the magnetic field, \( B \), was calibrated, the effective mass of the carriers was directly determined by following the positions of the peaks in \( B \) vs. \( f \). The effective mass was found to equal the cyclotron resonance mass within experimental error. The results were reproducible in two separate samples of high mobility GaAs/AlGaAs heterostructures.

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