Evidence for effective mass reduction in GaAs/AlGaAs quantum wells

A. T. Hatke,¹ M. A. Zudov,¹* J. D. Watson,²,³ M. J. Manfra,²,³ L. N. Pfeiffer,⁴ and K. W. West⁴

¹School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA
²Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA
³Birck Nanotechnology Center, School of Materials Engineering and School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA
⁴Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA

(Received 15 February 2012; revised manuscript received 6 April 2013; published 26 April 2013)

We have performed microwave photoresistance measurements in high mobility GaAs/AlGaAs quantum wells and investigated the value of the effective mass. Surprisingly, the effective mass, obtained from the period of microwave-induced resistance oscillations, is found to be about 12% lower than the band mass in GaAs, m⋆.

This finding provides strong evidence for electron-electron interactions which can be probed by microwave photoresistance in very high Landau levels. In contrast, the measured magnetoplasmon dispersion revealed an effective mass which is close to m⋆, in accord with previous studies.

DOI: 10.1103/PhysRevB.87.161307 PACS number(s): 73.43.Qt, 73.40.–c, 73.63.Hs

The most frequently quoted value of the effective mass m⋆ in GaAs/AlGaAs-based two-dimensional electron systems (2DES) is the value of the band mass of bulk GaAs, m⋆ ≈ 0.067m0 (m0 is the free electron mass).¹ One of the oldest and still frequently employed experimental methods to obtain m⋆ is based on Shubnikov–de Haas oscillations (SdHOs).²,³ Being a result of Landau quantization in a magnetic field B, SdHOs are controlled by the filling factor

φ = eB/m⋆,ne/

where

εF = e2π/ℏnF/m⋆, e is the charge, ω is the cyclotron energy, nF is the carrier density, and ωm⋆ = eB/m⋆ is the cyclotron energy. Since m⋆ does not enter the filling factor, it cannot be obtained from the oscillation period but, instead, one has to analyze the temperature damping of the SdHO amplitude.

The SdHO approach applied to 2DES with ne ≥ 10¹¹ cm⁻² usually yields m⋆ values which are close to, or somewhat higher than, m⋆.⁴,⁵ However, there exist studies⁶,⁷ which report values significantly (≥10%) lower than m⋆. The disagreement in obtained mass values can, at least in part, be accounted for by a relatively low accuracy of the SdHO approach.⁸ There also exist other factors which can affect extracted m⋆, even when the procedure seems to work properly.⁹,¹⁰ According to Ref. 7, the lower values of m⋆ might very well be a signal of electron-electron interactions which, in contrast to the case of dilute 2DES, can actually reduce the effective mass at intermediate densities.¹¹⁻¹³ Therefore, it is both interesting and important to revisit the issue of low effective mass values using alternative experimental probes, which we do in this Rapid Communication.

In addition to SdHOs, several other types of magnetoresistance oscillations are known to occur in high mobility 2DES.¹⁶⁻⁻¹⁸ Unlike the filling factor entering SdHOs, the parameters controlling these oscillations do depend on m⋆, thus making it available directly from the oscillation period. In what follows, we briefly discuss one such oscillation type, microwave-induced resistance oscillations (MIROs),¹⁹ whose period can be measured with high precision.

MIROs appear in magnetoresistivity when a 2DES is irradiated by microwaves. Being a result of electron transitions between Landau levels owing to photon absorption, MIROs are controlled by ω/ωc, where ω = 2πf is the radiation frequency. It is well established both theoretically²⁶⁻⁻²⁹ and experimentally,³⁰⁻⁻³⁴ that MIROs can be described by

−sin(2πω/ωc), provided that 2πω/ωc ≫ 1 and that the microwave power is not too high.³⁵ As a result, the higher order (i = 3, 4, . . .) MIRO maxima are accurately described by

ωm⋆ = eBi/4m0(1 − δ),

where Bi is the magnetic field of the ith maximum and δ ≈ 1/4.³⁷ Once the value of δ is verified experimentally, one can obtain m⋆ using, e.g., the dispersion of the ith MIRO maximum f(Bi).³⁸ Equivalently, the mass can be obtained directly from the oscillation period at a given ω, e.g., from the dependence of i on Bi, i = oωm⋆/eBi + δ.

In this Rapid Communication we investigate the effective mass in very high mobility GaAs/AlGaAs quantum wells using microwave photoresistance measurements performed over a wide frequency range from 100 to 175 GHz. Remarkably, the effective mass extracted from MIROs is found to be considerably lower than the band mass value. More specifically, MIROs are found to be well described by Eq. (1) with the effective mass m⋆ ≈ 0.059m0 at all frequencies studied. These findings provide strong evidence for electron-electron interactions which can be probed by microwave photoresistance in very high Landau levels. In contrast, the measured dispersion of the magnetoplasmon resonance (MPR) reveals m⋆ ≈ m⋆, in agreement with previous studies.

Our sample A (sample B) is a lithographically defined Hall bar of width wA = 50 μm (wB = 200 μm) fabricated from a 300-Å-wide GaAs/Al0.24Ga0.76As quantum well grown by molecular beam epitaxy at Purdue (Princeton). The low-temperature density and mobility of sample A (sample B) were nA ≈ 2.7 × 10¹¹ cm⁻² (nB ≈ 3.2 × 10¹¹ cm⁻²) and μA ≈ 1.3 × 10⁷ cm²/V s (μB ≈ 1.1 × 10⁷ cm²/V s), respectively. Microwave radiation, generated by a backward wave oscillator, was delivered to the sample placed in a ⁴He cryostat via a 1/4-in.- (6.35-mm)-diam light pipe. The resistivity ρω was measured under continuous microwave irradiation using a standard low-frequency lock-in technique.
data we have then extracted the magnetic field positions of the MIRO maxima and of the MPR peak for all frequencies studied. Our findings are presented in Fig. 1(b) showing microwave frequency $f$ as a function of $B$ corresponding to $i = 3, 4$ MIRO maxima (solid circles) and to the MPR peak (open circles). It is clear that the MIRO maxima follow the expected linear dispersion relation, which extrapolates to the origin, as expected from Eq. (1). By fitting the data (dotted lines) with Eq. (1), $f = (i - 1/4) e B_i / 2 \pi m^*,$ we obtain $m^* = 0.0586 m_0$ and $m^* = 0.0587 m_0$ for $i = 3$ and $i = 4,$ respectively. Since the obtained values are both very close to each other, we conclude that the effective mass $m^* \approx 0.059 m_0$ accurately describes MIRO in sample A.

On the other hand, the MPR peak follows a dispersion [cf. open circles in Fig. 1(b)] characteristic of a magnetoplasmon resonance, $^{34}$

$$\omega^2 = \omega^2_0 + \omega^2_b,$$

where $\omega_0$ is the frequency of the lowest mode of standing plasmon oscillation. As shown in the inset, $f^2$ is a linear function of $B^2,$ in agreement with Eq. (2). From the slope of the fit to the data with $f^2 = f^2_0 + (e B / 2 \pi m^*)^2,$ (cf. solid line in the inset) we obtain $m^* \approx 0.066 m_0.$ We also notice that previous MPR experiments obtained $m^*$ values ranging from 0.067 to 0.071. 

Using $\omega_0 \approx 0.85 \sqrt{\pi e^2 n_c / 2 \epsilon_0 \delta m^* w},$ we estimate $f_0 \approx 65$ GHz. This value is in good agreement with $f_0 \approx 112$ GHz obtained from the value of the fit at $B^2 = 0.$ The MPR dispersion $f(B)$ [cf. solid curve in Fig. 1(b)], calculated using Eq. (2) and extracted $f_0$ and $m^*$, shows excellent agreement with our experimental data. We thus conclude that the peak marked by “MPR” in Fig. 1(a) originates from the fundamental MPR mode. 

The main conclusion of our study on sample A is that the effective mass obtained from MIROs is significantly lower than both the mass entering the magnetoplasmon resonance and the band mass in GaAs. To confirm this finding we have performed similar measurements on sample B. Figure 2(a) shows $\rho_{xx}(B)$ measured at $T = 0.5$ K in sample B under microwave irradiation of frequency $f = 170$ GHz. We also notice a series of fast oscillations superimposed on the second MIRO maximum. The origin of these oscillations is unknown at this point, but the peak closest to the second harmonic of the cyclotron resonance (marked by “$X_2$”) looks similar to the recently discovered radiation-induced $X_2$ peak. 

One can accurately determine the effective mass entering Eq. (1) by trial and error, namely, by adjusting $m^*$ until each calculated cyclotron resonance harmonic falls symmetrically between maximum and minimum of the same order. Remarkably, such a procedure applied to the data in Fig. 1(a) results in $m^* = 0.059 m_0,$ used to calculate the positions of vertical lines (marked by $i$) drawn at $\omega / \omega_c = i = 2, 3, 4, \ldots.$ The obtained value is considerably ($\approx 12\%$) lower than $m^*_c = 0.067 m_0$ and its confirmation warrants further investigation.

To this end, and to confirm that the strong peak in Fig. 1(a) is due to MPR, we have repeated our measurements at a variety of microwave frequencies, from 100 to 175 GHz. From these
fields strongly support the notion that the $\chi_2$ peak and MIROs are two different phenomena. However, there exists a controversy regarding its exact position. More specifically, Refs. 50 and 51 concluded that the $\chi_2$ peak occurs exactly at the second harmonic of the cyclotron resonance, $\omega_0/\omega_c = 2$. However, Refs. 36, 52, and 53 found that the peak occurs at somewhat higher $B$ than the second harmonic. This apparent controversy can be resolved by noticing that the above conclusions were made based on different approaches. While Ref. 50 has determined the $\chi_2$ peak position from the cyclotron resonance measured in absorption, Refs. 36, 52, and 53 used MIROs as a reference. Indeed, using the latter approach we find that the $\chi_2$ peak occurs at a magnetic field somewhat higher than the second harmonic, as in previous studies.36,52,53

On the other hand, we have just established that the MIRO effective mass is significantly lower than the mass entering the MPR, which is closely related to the cyclotron resonance. Therefore it is interesting to examine the effective mass obtained from the $\chi_2$ peak, assuming that it appears exactly at the second harmonic of the cyclotron resonance, as found in Refs. 50 and 51. As shown in Fig. 2(b) by open circles, the $\chi_2$ peak follows a linear dispersion relation extrapolating through the origin. A linear fit with $f = eB/\pi m^*$, shown by the solid line, generates $m^* = 0.063 m_0$, which is noticeably higher (lower) than the MIRO (MPR) mass.

As mentioned above, one can also obtain $m^*$ directly from the MIRO period. This method is based on scaling of multiple oscillations and does not a priori assume $\delta = 1/4$. To illustrate this approach, we present on the right axis of Fig. 3 microwave photoresistivity $\delta \rho_0$ (right axis, solid curve) and the order of the MIRO maxima $i$ (left axis, circles) vs $1/B$ measured in sample A at (a) $f = 130$ GHz and (b) $f = 160$ GHz. Fits to the data (solid lines) with $i = 2 \pi f m^* / eB + \delta$ yield $\delta \approx 0.25$ and $m^* \approx 0.0585 m_0$ ($m^* \approx 0.0587 m_0$) for $f = 130$ GHz ($f = 160$ GHz). Dashed lines are calculated using Eq. (1) and $m^* = m_0^* = 0.067 m_0$.

We summarize our findings in Fig. 4, showing effective mass values, obtained from the dispersion relations of different phenomena, as a function of microwave frequency. More specifically, $m^*$ obtained from the MIRO maxima for $i = 3$ (open circles) and $i = 4$ (solid circles) measured in samples A and B are shown in Figs. 4(a) and 4(b), respectively. In addition, Fig. 4(a) shows $m^*$ obtained from the MPR (squares), while Fig. 4(b) shows $m^*$ from the $\chi_2$ peak, assuming that it occurs at the second cyclotron resonance harmonic. Solid horizontal lines represent the averages of the measured values (see the figure caption) and dashed horizontal lines are drawn.
FIG. 4. (Color online) (a) $m^*$ obtained from the MIRO maxima for $i = 3$ (open circles), $i = 4$ (solid circles), and the MPR peak (squares) vs $f$ measured in sample A. Solid lines represent averages for the $i = 4$ MIRO maxima, $m^* = 0.0587 m_0$, and for the MPR peak, $m^* = 0.0664 m_0$, respectively. (b) $m^*$ obtained from the MIRO maxima for $i = 3$ (open circles), $i = 4$ (solid circles), and from the $\chi^2$ peak (crosses) vs $f$ measured in sample B. Solid lines represent averages for the $i = 4$ MIRO maxima, $m^* = 0.0586 m_0$, and for the $\chi^2$ peak $m^* = 0.0629 m_0$ (see text), respectively. In both plots, the dashed line represent $m^*_0 = 0.067 m_0$.

We thank M. Dyakonov and B. Shklovskii for discussions, and J. Jaroszynski, J. Krzyztek, G. Jones, T. Murphy, and D. Smirnov for technical assistance. This work was supported by the US Department of Energy, Office of Basic Energy Sciences, under Grants No. DE-SC002567 (Minnesota) and No. DE-SC0006671 (Purdue). A portion of this work was performed at the National High Magnetic Field Laboratory (NHMFL), which is supported by NSF Cooperative Agreement No. DMR-0654118, by the State of Florida, and by the DOE. The work at Princeton was partially funded by the Gordon and Betty Moore Foundation and the NSF MRSEC Program through the Princeton Center for Complex Materials (DMR-0819860).

"Corresponding author: zudov@physics.umn.edu"
EVIDENCE FOR EFFECTIVE MASS REDUCTION IN . . .

PHYSICAL REVIEW B 87, 161307(R) (2013)


Strictly speaking, “1/4” in Eq. (1) should be replaced by $\delta_i$ which approaches 1/4 for $i \geq 3$. For instance, according to Ref. 36, $\delta_i \approx 0.23$ and $\delta_i \approx 0.24$. However, using 1/4 in Eq. (1) instead of more accurate values is well justified since it will result in a less than 1% error in the mass.

Alternatively, $m^*$ can be obtained from (a) the MIRO minima, described by $\omega = \omega_0 (i + 1/4)$, (b) the zero-response nodes, $\omega = \omega_0 i$, where microwave photoresistance vanishes, or (c) directly from the oscillation period, which can be found from the positions of, e.g., $i$th and $(i + 1)$th maxima.


Equation (2) is valid when the retardation effects can be ignored, i.e., when $\alpha = \sqrt{ek_\text{F}^2/2\pi e\hbar m^*c^2} < 1$ (Refs. 59 and 60). In sample A, we estimate $\alpha \approx 0.15$.

This value is lower than $m^* = 0.066$ obtained in Ref. 50.

Similar $m^*$ values have been obtained from the MIRO minima and from the zero-response nodes (not shown).

