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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

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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 magneto-plasmon dispersion revealed an effective mass which is close to \( m_B^* \), in accord with previous studies.

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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, \( m_B^* = 0.067 m_0 \) (\( m_0 \) 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 (SdHO).2,3 Being a result of Landau quantization in a magnetic field \( B \), SdHO are controlled by the filling factor, \( \nu = 2e \delta / h \omega_c \), where \( \varepsilon_F = \pi \hbar^2 n_e / m^* \) is the Fermi energy, \( n_e \) is the carrier density, and \( \hbar \omega_c = eB / m^* \) 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 \( n_e \gtrsim 10^{11} \) cm\(^{-2} \) usually yields \( m^* \) values which are close to, or somewhat higher than, \( m_B^* \).4,5 However, there exist studies6,7 which report values significantly (\( \gtrsim 10 \%) \) lower than \( m_B^* \). 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 might affect extracted \( m^* \), even when the procedure seems to work properly.6,9–11 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.12–17 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 Letter.

In addition to SdHO, several other types of magnetoresistance oscillations are known to occur in high mobility 2DES.18–25 Unlike the filling factor entering SdHO, 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 (MIRO),19 whose period can be measured with high precision.

MIRO appear in magnetoresistivity when a 2DES is irradiated by microwaves. Being a result of electron transitions between Landau levels owing to photon absorption, MIRO are controlled by \( \omega / \omega_c \), where \( \omega = 2\pi f \) is the radiation frequency. It is well established both theoretically26–30 and experimentally,31–34 that MIRO can be described by \( -\sin(2\pi \omega / \omega_c) \), provided that \( 2\pi \omega / \omega_c \gg 1 \) and that the microwave power is not too high.35 As a result, the higher order (\( i = 3, 4, \ldots \)) MIRO maxima are accurately36 described by

\[
\omega = \frac{e}{m^*} B_i (i - \delta),
\]

where \( B_i \) is the magnetic field of the \( i \)-th maximum and \( \delta \approx 1/4 \).37 Once the value of \( \delta \) is verified experimentally, one can obtain \( m^* \) using, e.g., the dispersion of the \( i \)-th MIRO maximum, \( f(B_i) \).38 Equivalently, the mass can be obtained directly from the oscillation period at a given \( \omega \), e.g., from the dependence of \( i \) on \( B_i \), \( i = \omega m^* / eB_i + \delta \).

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 GHz to 175 GHz. Remarkably, the effective mass extracted from MIRO is found to be considerably lower than the band mass value. More specifically, MIRO are found to be well described by Eq. (1) with the effective mass \( m^* \approx 0.059 m_0 \) 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 magneto-plasmon resonance (MPR) reveals \( m^* \approx m_B^* \), in agreement with previous studies.

Our sample A (sample B) is a lithographically defined Hall bar of width \( w_A = 50 \mu m \) (\( w_B = 200 \mu m \)) fabricated from a 300 Å-wide GaAs/Al\(_{0.24}\)Ga\(_{0.76}\)As quantum well grown by molecular beam epitaxy at Purdue (Princeton). The low-temperature density and mobility of sample A (sample B) were \( n_A \approx 2.7 \times 10^{11} \) cm\(^{-2} \) (\( n_B \approx 3.2 \times 10^{11} \) cm\(^{-2} \)).
cm$^{-2}$) and $\mu_A \approx 1.3 \times 10^7$ cm$^2$/Vs ($\mu_B \approx 1.1 \times 10^7$ cm$^2$/Vs), respectively. Microwave radiation, generated by a backward wave oscillator, was delivered to the sample placed in a $^3$He cryostat via a 1/4" (6.35 mm)-diameter light pipe. The resistivity $\rho_\omega$ was measured under continuous microwave irradiation using a standard low-frequency lock-in technique.

In Fig. 1(a) we present the magnetoresistivity $\rho_\omega(B)$ measured at $T = 0.65$ K in sample A under microwave irradiation of frequency $f = 170$ GHz. The data reveal giant negative magnetoresistance effect, pronounced MIRO, zero-resistance states, and a strong peak (marked by “MPR”) which corresponds to the lowest mode of the dimensional magneto-plasmon resonance. Finally, we 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 “$\chi_2^-$”) looks similar to the recently discovered radiation-induced $\chi_2^-$ peak. We will return to this peak when we discuss our results in sample B.

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 $\omega/\omega_c = \bar{f} = 2, 3, 4, \ldots$. The obtained value is considerably ($\approx 12\%$) lower than $m^*_2 = 0.067 m_0$ 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 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), $f = (i-1/4)eB_i/2\pi m^*$, we obtain $m^* = 0.0586 m_0$ and $m^* = 0.0587 m_0$ for $i = 3$ and $i = 4$, respectively. Since 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 magneto-plasmon resonance,\textsuperscript{54}

$$\omega^2 = \omega_c^2 + \omega_0^2,$$

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 $f^2 = f_0^2 + (eB/2\pi m^*)^2$ (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.\textsuperscript{47,48,55–57}

Using $\omega_0 \approx 0.85 \sqrt{\pi \varepsilon \varepsilon_0 n_0/2e^2 \varepsilon m^*}$,\textsuperscript{47,58–61} where $m^* = 0.066 m_0$, $\varepsilon_0$ is the permittivity of vacuum, and $\varepsilon = 6.9$ is the average dielectric constant of GaAs (12.8) and free space (1), we estimate $f_0 = \omega_0/2\pi = 105$ GHz. This value is in good agreement with $f_0 = 112$ 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.\textsuperscript{47–49}

The main conclusion of our study on sample A is that the effective mass obtained from MIRO is significantly lower than both the mass entering magneto-plasmon resonance and the band mass in GaAs. To confirm this finding we have performed similar measurements on sample B. Figure 2(a) shows $\rho_\omega(B)$ measured at $T = 0.5$ K in sample B under microwave irradiation of $f = 170$ GHz. Following the procedure of trial and error, we again find that aligning MIRO with the harmonics of cyclotron resonance (cf. vertical lines), calls for a low value of the
effective mass, \( m^* = 0.059 m_0 \). By repeating the measurements at different \( f \) from 100 to 175 GHz, we have obtained the dispersion relations for the \( i = 3 \) and \( i = 4 \) MIRO maxima which are shown in Fig. 2(b) as solid circles. The linear fits with \( f = (i - 1/4)eB_i/2\pi m^* \), generate \( m^* = 0.0584 m_0 \) and \( m^* = 0.0586 m_0 \) for \( i = 3 \) and \( i = 4 \), respectively. We thus again find a considerably reduced effective mass value which nearly matches our result in sample A.

Close examination of Fig. 2(a) reveals that the photore sistance maximum near the second harmonic of the cyclotron resonance is considerably higher and sharper than all other maxima. We attribute this maximum to the \( X_2 \) peak recently discovered in high mobility 2DES.\(^{36,50-53}\) While the origin of the \( X_2 \) peak remains unknown, its large amplitude\(^{50,52}\) and distinct responses to dc\(^{53}\) and to in-plane magnetic\(^{31}\) fields strongly support the notion that the \( X_2 \) peak and MIRO are two different phenomena. However, there exists a controversy regarding its exact position. More specifically, Refs. 50, 51 concluded that the \( X_2 \) peak occurs \textit{exactly} at the second harmonic of the cyclotron resonance, \( \omega/\omega_c = 2 \). However, Refs. 36, 52, 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 \( X_2 \) peak position from the cyclotron resonance measured in absorption, Refs. 36, 52, 53 used MIRO as a reference. Indeed, using the latter approach we find that the \( X_2 \) peak occurs at a magnetic field somewhat higher than the second harmonic, like 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 MPR, which is closely related to the cyclotron resonance. Therefore it is interesting to examine the effective mass obtained from the \( X_2 \) peak, assuming that it appears \textit{exactly} at the second harmonic of the cyclotron resonance, as found in Refs. 50, 51. As shown in Fig. 2(b) by open circles, the \( X_2 \) 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 in the introduction, one can also obtain \( m^* \) directly from the MIRO period. This method is based on scaling of multiple oscillations and does not \textit{a priori} assume \( \delta = 1/4 \). To illustrate this approach, we present on the right axis of Fig. 3 microwave photore sistivity \( \delta \rho_{\omega} = \rho_{\omega} - \rho \) as a function of \( 1/B \) measured at (a) \( f = 130 \) GHz and (b) \( f = 160 \) GHz. Both data sets exhibit multiple oscillations whose period scales with \( 1/m^* f \). To extract \( m^* \) from the data, we plot the order of the MIRO maxima \( i \) (circles, left axis) as a function of \( 1/B \) for both frequencies and observe expected linear
dependence. From the slope of the linear fits to the data (solid lines), \( i = 2\pi f m^* / eB + \delta \), we find \( m^* \approx 0.0585 m_0 \) \( (m^* \approx 0.0587 m_0) \) for \( f = 130 \text{ GHz} \) \( (f = 160 \text{ GHz}) \).63 These values are in excellent agreement with the \( m^* \) values found from the dispersions of the \( i = 3, 4 \) MIRO maxima (cf. Figs. (1), (2)). In addition, we find that both fits intercept the vertical axis at \( \delta \approx 0.25 \), in agreement with Eq. (1), confirming the equivalence of two approaches. Finally, to illustrate that our data cannot be described by the band mass we include dashed lines which are calculated using \( i = 2\pi f m^*_b / eB + 0.25 \).

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), \( i = 4 \) (filled circles) measured in sample A and sample B are shown in Fig. 4(a) and Fig. 4(b), respectively. In addition, Fig. 4(a) shows \( m^* \) obtained from the MPR (squares), while Fig. 4(b) shows \( m^* \) from the \( X_2 \) peak, assuming that it occurs at the second cyclotron resonance harmonic. Solid horizontal lines represent the averages of the measured values (see figure caption) and dashed horizontal lines are drawn at \( m^*_b = 0.067 m_0 \). Figure 4 further confirms that the masses extracted from the fits in Fig. 1(b) and Fig. 2(b) accurately describe our experimental data over the entire range of frequencies studied.

In summary, we have investigated microwave photore sistance in very high mobility GaAs/AlGaAs quantum wells over a wide range of microwave frequencies. The analysis of the period of microwave-induced resistance oscillations reveals an effective mass \( m^* \approx 0.059 m_0 \), which is considerably lower than the GaAs band mass \( m^*_b = 0.067 m_0 \). These findings provide strong evidence for electron-electron interactions in very high Landau levels and for sensitivity of MIRO to these interactions. On the other hand, the measured dispersion of the magneto-plasmon resonance is best described by \( m^* \approx m^*_b \). It would be interesting to examine if the low value of the effective mass is confirmed in studies of other nonlinear phenomena, such as Hall-field induced resistance oscillations.20,64–66

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* Corresponding author: zudov@physics.umn.edu


8 At \( n_c \approx 3 \times 10^{11} \text{ cm}^{-2} \), Ref. 6 (Ref. 7) obtained \( m^* \) between \( \approx 0.0615 \) \( (\approx 0.0575) \) and \( \approx 0.0655 \), including error bars.


37. Strictly speaking, “1/4” in Eq. (1) should be replaced by \( \delta_1 \) which approaches 1/4 for \( i \gtrsim 3 \). For instance, according to Ref. 36, \( \delta_1 \approx 0.23 \) and \( \delta_2 \approx 0.24 \). However, using 1/4 in Eq. (1) instead of more accurate values is well justified since it will result in less than 1% error in the mass.
38. Alternatively, \( m^* \) can be obtained from (a) the MIRO minima, described by \( \omega \approx \omega_c (i + 1/4) \), (b) the zero-response nodes, \( \omega \approx \omega_c \cdot i \), 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.
61. Equation (2) is valid when the retardation effects can be ignored, i.e. when \( \alpha = \sqrt{e^2 \hbar / 2 \pi \hbar \omega \gamma} \ll 1 \) (Refs. 59, 60). In sample A, we estimate \( \alpha \approx 0.15 \).
62. This value is lower than \( m^* \approx 0.066 \) obtained in Ref. 50.
63. Similar \( m^* \) values have been obtained from the MIRO minima and from the zero-response nodes (not shown).