Effective mass from microwave photoresistance measurements in GaAs/AlGaAs quantum wells

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Abstract. We have performed microwave photoresistance measurements in high mobility GaAs/AlGaAs quantum wells and investigated the value of the effective mass. The effective mass, obtained from the period of microwave-induced resistance oscillations (MIRO), was found to be about 12% lower than the band mass in GaAs, \( m^\star_b \). In contrast, the measured magneto-plasmon dispersion (MPR) revealed an effective mass which is close to \( m^\star_b \), in accord with previous studies. These findings suggest that, in contrast to MPR, the MIRO dispersion contains corrections due to electron-electron interaction effects.

1. Introduction

The most frequently quoted value of the effective mass \( m^\star \) in GaAs/AlGaAs-based two-dimensional electron systems (2DESs) is the value of the band mass of bulk GaAs, \( m^\star_b = 0.067m_0 \), where \( m_0 \) is the free electron mass [1]. One of the common methods to obtain \( m^\star \) is based on the temperature damping of Shubnikov-de Haas oscillations (SdHOs) [2], which are controlled by the filling factor, \( \nu = 2\varepsilon_F/h\omega_c \), where \( \varepsilon_F = \pi\hbar^2n_e/m^\star \) is the Fermi energy, \( n_e \) is the carrier density, \( h\omega_c = eB/m^\star \) is the cyclotron energy, and \( B \) is the magnetic field. Since \( m^\star \) does not enter the filling factor, it cannot be obtained from the oscillation period; instead, one has to analyze the temperature damping of the SdHO amplitude.

The SdHO approach applied to 2DESs with \( n_e \gtrsim 10^{11} \text{ cm}^{-2} \) usually yields \( m^\star \) values which are close to, or somewhat higher than, \( m^\star_b \) [3, 4]. However, there exist studies [5,6] which report values significantly (\( \sim 10 \% \)) lower than \( m^\star_b \). The disagreement in obtained mass values can, at least in part, be accounted for by a relatively low accuracy of the SdHO approach.¹ There also exist other factors which might affect extracted \( m^\star \), even when the procedure seems to work properly, which itself is not always the case [5,7–9]. According to Ref. [6], the lower values of \( m^\star \) might very well be a signal of electron-electron interactions which, in contrast to the case of dilute 2DESs, can actually reduce the effective mass at intermediate densities [10–15].

¹ At \( n_e \sim 3 \cdot 10^{11} \text{ cm}^{-2} \), Ref. [5] (Ref. [6]) obtained \( m^\star \) between 0.061 (0.057) and 0.065, including error bars.
Therefore, it is both interesting and important to revisit the issue of low effective mass values using alternative experimental probes.

In addition to SdHOs, several other types of magnetoresistance effects are known to occur in high mobility 2DESs [16–23]. 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 (MIRO) [16], 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 theoretically [24–27] and experimentally [28–30], that MIRO are well described by $-\sin(2\pi \omega/\omega_c)$, provided that $2\pi \omega/\omega_c \gg 1$ and one is in the low power limit [31,32]. As a result, the higher order ($i = 3, 4, \ldots$) MIRO maxima are accurately described by

$$\omega = m^* B_i (i - \delta),$$

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

In this work we investigate the effective mass in a high mobility GaAs/AlGaAs quantum well using microwave photoresistance measured over a wide frequency range from 100 to 175 GHz. Remarkably, the effective mass extracted from the 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 the magneto-plasmon resonance (MPR) reveals $m^* \approx m_0^*$, in agreement with previous studies.

2. Experimental details

Our sample is a lithographically defined Hall bar of width $w = 50 \mu m$ fabricated from a 300 Å-wide GaAs/Al$_{0.24}$Ga$_{0.76}$As quantum well grown by molecular beam epitaxy with a density and mobility of $n \approx 2.7 \times 10^{11} \text{ cm}^{-2}$ and $\mu \approx 1.3 \times 10^7 \text{ cm}^2/\text{Vs}$, 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 magnetoresistivity $\rho_{\omega}(B)$ was measured under continuous microwave irradiation using a standard low-frequency lock-in technique.

3. Results and discussion

In Fig. 1(a) we present $\rho_{\omega}(B)$ measured at $T = 0.65$ K under microwave irradiation of $f = 170$ GHz. The data reveal MIRO, zero-resistance states [34–39], sharp spikes near the second harmonic of the cyclotron resonance [40–42], and a peak which corresponds to the lowest mode of the dimensional magneto-plasmon resonance (MPR) [43–45]. One can determine the effective mass entering Eq. (1) by trial and error, namely, by adjusting $m^*$ until each cyclotron resonance harmonic falls symmetrically between maximum and minimum of the same order. Remarkably,

\[ \delta \approx 1/4 \]

\[ \delta_0 \approx 0.23 \text{ and } \delta_1 \approx 0.24. \]

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.

Alternatively, $m^*$ can also be obtained from the MIRO minima, described by $\omega = \omega_C (i + 1/4)$, or from the zero-response nodes, $\omega = \omega_C - i$, where microwave photoresistance vanishes.

\[ m^* \approx 0.059 m_0 \]
such a procedure applied to the data in Fig. 1(a) results in \( m^\star \approx 0.059 m_0 \), used to calculate the positions of vertical lines drawn at \( \omega/\omega_\text{c} = 2, 3, 4, \text{ and } 5 \).

We have repeated our measurements at various microwave frequencies, from 100 to 175 GHz, and obtained the magnetic field positions of the MIRO maxima and of the MPR peak. Our findings are presented in Fig. 1(b) showing microwave frequency \( f \) as a function of \( B \) corresponding to the MIRO maxima at \( i = 3 \) (open circles), \( i = 4 \) (filled circles), and to the MPR peak (squares). It is clear that the MIRO maxima follow a linear dispersion relation, which extrapolates to the origin, as expected from Eq. (1). By fitting the MIRO data with Eq. (1), \( f = (i - 1/4)eB_\text{l}/2\pi m^\star \), we obtain \( m^\star \approx 0.0586 m_0 \ (m^\star \approx 0.0587 m_0 \) for \( i = 3 \) \((i = 4)\). Since the obtained values are both very close to each other, we conclude that the effective mass entering the MIRO period is given by \( m^\star \approx 0.059 m_0 \).

The MPR peak follows a dispersion [cf. open squares in Fig. 1(b)] characteristic of a magnetoplasmon resonance [46],

\[
\omega^2 = \omega_0^2 + \omega_\text{c}^2,
\]

where \( \omega_0 \) is the frequency of the lowest mode of standing plasmon oscillation (with a wavevector determined by the Hall bar width). As shown in the inset, \( f^2 = f_0^2 + (\omega B/2\pi m^\star)^2 \) (cf. solid line in the inset), we obtain \( m^\star \approx 0.066 m_0 \approx m^\star_0 \). We also notice that previous MPR experiments obtained \( m^\star \) values ranging from 0.067 to 0.071 [43, 44, 47–49].

We summarize our findings in Fig. 1(c) showing effective mass values, obtained from the two dispersion relations, as a function of microwave frequency. More specifically, \( m^\star \) obtained from the MIRO maxima for \( i = 3 \) (open circles), \( i = 4 \) (filled circles), and from the MPR (squares). Solid horizontal lines represent the averages of the measured values. Figure 1(c) further confirms that the masses extracted from our fits accurately describe our experimental data over the entire range of frequencies studied.

As mentioned above, one can also easily obtain \( m^\star \) from the MIRO period. This method is based on the scaling of multiple oscillations and does not a priori assume \( \delta = 1/4 \). To illustrate this approach, we present in Fig. 2 microwave photoresistivity \( \delta \rho_\text{p} = \rho_\text{p} - \rho \) (right axis) as a

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**Figure 1.** (Color online) (a) Magnetoresistivity \( \rho_\text{p}(B) \) measured at \( T = 0.65 \) K irradiated with microwaves of \( f = 170 \) GHz. The vertical lines (marked by \( i \)) are drawn at the harmonics of the cyclotron resonance, \( \omega/\omega_\text{c} = i \), calculated using \( m^\star = 0.059 m_0 \). (b) Dispersions \( f(B) \) of the MIRO maxima for \( i = 3 \) (open circles), \( i = 4 \) (filled circles), and of the MPR peak (squares). The lines are fits to the MIRO data, \( f = (i - 1/4)eB_\text{l}/2\pi m^\star \), with \( i = 3, 4 \) and the solid curve is given by \( f = \sqrt{f_0^2 + (eB/2\pi m^\star)^2} \), where \( f_0 = 112.5 \) GHz and \( m^\star = 0.066 m_0 \). Inset shows the MPR dispersion as \( f^2 vs B^2 \) (squares) and a linear fit (solid line), \( f^2 = f_0^2 + (eB/2\pi m^\star)^2 \). (c) \( m^\star \) obtained from the MIRO maxima for \( i = 3 \) (open circles), \( i = 4 \) (filled circles) and the MPR peak (squares) vs \( f \). Solid lines represent averages for the \( i = 4 \) MIRO maxima, \( m^\star = 0.0587 m_0 \) and for the MPR peak, \( m^\star = 0.0664 m_0 \), respectively.
Figure 2. (Color online) Microwave photoresistivity $\delta \rho_\omega$ (right axis, solid curve) and the order of the MIRO maxima $i$ (left axis, circles) vs. $1/B$ measured 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 $m^* = m^*_b = 0.067 m_0$.

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 $1/(f m^*)$. 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 the 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 $f = 130$ GHz ($f = 160$ GHz). These values are in excellent agreement with the $m^*$ values found from the dispersions of the $i = 3, 4$ MIRO maxima. 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 the two approaches. Finally, to illustrate that our data cannot be described by the band mass we include dashed lines which are calculated using $i = 2\pi f m^*_b/eB + 0.25$.

4. Summary

In summary, we have investigated microwave photoresistance in a high mobility GaAs/AlGaAs quantum well over a wide range of microwave frequencies. The analysis of the period of the 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 and for sensitivity of MIRO to these interactions. On the other hand, the measured dispersion of the magneto-plasmon resonance is best described by $m^* = m^*_b$. 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 [18,50,51].

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$^5$ Similar $m^*$ values have been obtained from the MIRO minima and from the zero-response nodes (not shown).
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