Effect of an in-plane magnetic field on microwave photoresistance and Shubnikov-de Haas effect in high-mobility GaAs/AlGaAs quantum wells

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Effect of an in-plane magnetic field on microwave photoresistance and Shubnikov-de Haas effect in high-mobility GaAs/AlGaAs quantum wells

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Abstract. A recent study of the decay of microwave-induced resistance oscillations (MIRO) in GaAs/AlGaAs quantum wells due to an in-plane magnetic field $B_{\|}$ has revealed the dominant role of a quadratic-in-$B_{\|}$ correction to the quantum scattering rate. In the present study, we examine the evolution of Shubnikov-de Haas oscillations (SdHO) with increasing tilt angle in the same sample. Even though we find that the SdHO also diminish at high tilt angles, this decay is qualitatively different from that of MIRO, possibly indicating a different physical origin.

1. Introduction

Among a variety of transport phenomena [1–14] recently discovered in very high Landau levels of a high mobility two-dimensional electron gas (2DEG), microwave-induced resistance oscillations (MIRO) [1, 2] and zero-resistance states [5, 6] have received the most attention, both theoretically [15–23] and experimentally [24–41]. It is now well established that at low microwave power and in overlapping Landau levels, MIRO are described by [42]

$$\delta\rho(\epsilon) \propto -\epsilon\lambda^2 \sin 2\pi\epsilon, \qquad (1)$$

where $\epsilon = \omega/\omega_c$, $\omega = 2\pi f$ and $\omega_c = eB_\perp/m^\star$ are the microwave and cyclotron frequencies, respectively, $m^\star$ is the electron effective mass, $\lambda = \exp(-\pi/\omega_c\tau_q^0)$ is the Dingle factor, and τ_q^0 is the quantum lifetime. While τ_q^0 is often obtained from Shubnikov-de Haas oscillations (SdHO), this method often leads to underestimated τ_q^0, presumably, due to extra suppression of the SdHO amplitude by macroscopic density fluctuations [27]. MIRO, on the other hand, are not affected by such fluctuations and thus offer a preferred way to obtain the quantum lifetime. As a result, MIRO are an attractive tool to study the dependence of the quantum lifetime on $B_{\|}$, the understanding of which is important for other systems, such as lateral quantum dots [43].

The effect of $B_{\|}$ on MIRO has been investigated several years ago by two experimental groups [44, 45] with conflicting outcomes; in Ref. [44] MIRO remained unchanged up to $B_{\|} \simeq 1$ T, but in Ref. [45] MIRO were strongly suppressed by $B_{\|} \simeq 0.5$ T. Stimulated by this controversy,

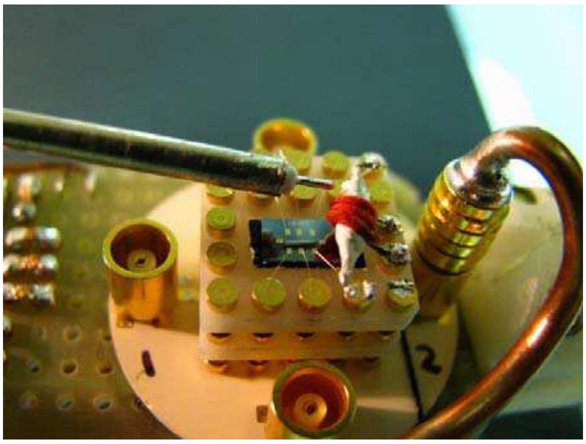

Figure 1. Photograph showing sample, 3 mm antenna, and an Allen Bradley carbon thermoresistor with DPPH, used to calibrate B.

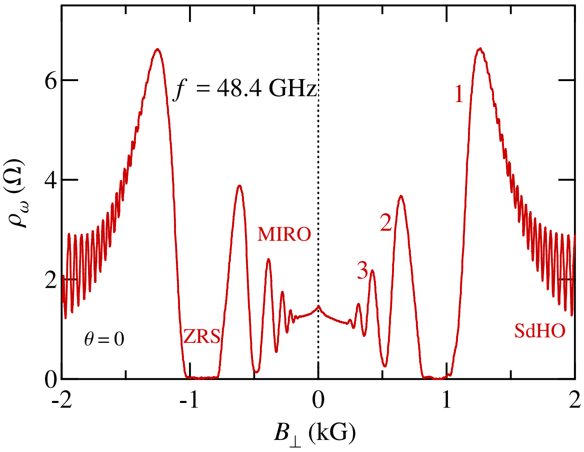

Figure 2. Magnetoresistivity $\rho_\omega(B_\perp)$ measured at $f = 48.4$ GHz, $T \simeq 0.3$ K, and $\theta = 0$, showing MIRO, a zero-resistance state, and SdHO.

we have revisited the issue [46] and found that the decay of the MIRO amplitude with increasing tilt angle can be understood in terms of a $B_\parallel$-induced increase of the single particle scattering rate, which acquires a quadratic-in-$B_\parallel$ correction. As a result of this correction, the lower order MIRO decay faster than the higher orders. Here, we extend our study, performed on the same sample, to the evolution of SdHO with increasing $B_\parallel$. As discussed below, SdHO also decay with increasing tilt angle, but, in contrast to MIRO, the decay appears to be roughly the same for all filling factors studied.

2. Experimental details

Our sample is a 200 μm-wide Hall bar etched from a symmetrically doped GaAs/$Al_{0.24}Ga_{0.76}As$ 30 nm-wide quantum well grown by molecular beam epitaxy. After illumination with a red light-emitting diode, the electron density and the mobility were $n_e \approx 3.6 \times 10^{11}$ cm^{-2} and $\mu \approx 1.3 \times 10^7$ cm^2/Vs, respectively. Microwave radiation of $f = 48.4$ GHz was delivered to the sample via a semirigid coaxial cable terminated with a 3 mm antenna (Fig. 1) [27, 32, 46]. A split-coil superconducting solenoid allowed us to change the magnetic field direction *in situ*, by rotating the ^{3}He insert, without disturbing the distribution of the microwave field. The resistivity was recorded using low-frequency (a few hertz) lock-in technique under continuous irradiation in sweeping magnetic field at a constant coolant temperature of $T \simeq 0.3$ K.

3. Experimental results and discussion

In Fig. 2 we present the magnetoresistivity $\rho_\omega(B_\perp)$ recorded at $\theta = 0°$, which shows pronounced MIRO and a well developed zero-resistance state, attesting to the high quality of our sample. MIRO orders are marked by integers. A Dingle plot analysis performed on these data reveals a quantum lifetime $\tau_q^0 = 21$ ps, which is typical of a high mobility 2DEG.

In Fig. 3 we present the resistivity ρ_ω as a function of the perpendicular field $B_\perp$ measured at different tilt angles: (a) $\theta = 57.5°$, (b) $\theta = 74.9°$, and (c) $\theta = 82.3°$. Each panel also includes the data recorded at $\theta = 0°$, demonstrating that the MIRO period depends only on the perpendicular component of the magnetic field, $B_\perp = B\cos\theta$, in agreement with earlier studies [44, 45]. At the same time, direct comparison with the $\theta = 0°$ data reveals that MIRO monotonically decay away with increasing tilt angle. As a result, the zero-resistance state is no longer observed at the highest angle.

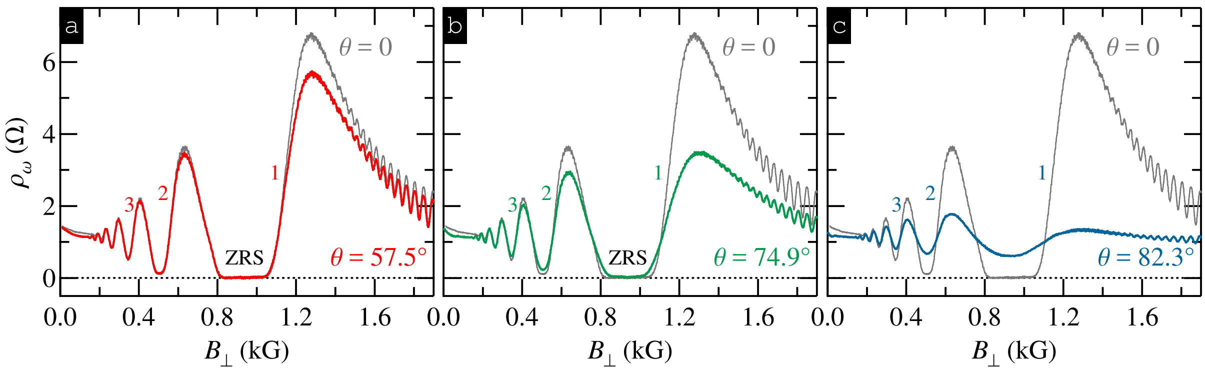

Figure 3. Magnetoresistivity $\rho_\omega(B_\perp)$ measured under microwave irradiation of $f = 48.4$ GHz at different tilt angles: (a) $\theta = 57.5°$, (b) $\theta = 74.9°$, and (c) $\theta = 82.3°$. For comparison each plot also contains $\rho_\omega(B_\perp)$ measured at $\theta = 0$. Adapted from Ref. [46].

The observed MIRO decay with increasing θ, however, is clearly not uniform and depends on the oscillation order (and, hence, on ϵ) [46]. For example, the data at $\theta = 57.5°$ and $\theta = 74.9°$ [Fig. 3(a) and Fig. 3(b), respectively], clearly reveal that the first (fundamental) oscillation decays faster then the second, and that there is virtually no suppression of higher order oscillations. As a result, in contrast to the data obtained at $\theta = 0°$, where the MIRO amplitude monotonically increases with $B_\perp$, the data obtained at higher tilt angles show more complicated behavior. Indeed, in the data obtained at $\theta = 82.3°$ [Fig. 3(c)], the first oscillation becomes considerably weaker than the second, while the second oscillation appears roughly the same as the third. At still higher tilt (not shown) the lower order oscillations virtually disappear, while the higher order (lower $B_\perp$) oscillations can still be observed. All these findings indicate that the degree of suppression is determined by an in-plane component of the magnetic field, $B_\parallel$. Indeed, the in-plane magnetic field is proportional to $B_\perp$, and, as a result, lower order (higher $B_\perp$) MIRO are subject to a larger $B_\parallel$ for a given θ.

As discussed in Ref. [46], the main mechanism of the MIRO decay in tilted magnetic fields appears to be the same as that responsible for the decay of Hall field-induced resistance oscillations [4, 47–49]. More specifically, the suppression of the oscillations can be interpreted in terms of a $B_\parallel$-induced correction to the quantum scattering rate, which is quadratic in $B_\parallel$ [49],

$$1/\tau_q = 1/\tau_q^0 + \delta(1/\tau_q)\,, \quad \delta(1/\tau_q) = (1/\tau_q{}^0)\cdot(B_\parallel/B_0)^2\,. \tag{2}$$

Here, $\delta(1/\tau_q)$ is the correction to the zero-tilt scattering rate $1/\tau_q^0$, induced by $B_\parallel$, and B_0 is a characteristic in-plane magnetic field, which corresponds to doubling of the quantum scattering rate. As the obtained B_0 is a few kG [46, 49], the increase of $1/\tau_q$ may be relevant to such areas as spin-based quantum computing [43, 50], where parallel fields of several Tesla are typical.

Further examination of the data in Fig. 3 reveals that SdHO also monotonically diminish with increasing tilt angle. To compare the decays of MIRO and SdHO, we construct Fig. 4, which shows (a) MIRO amplitude and (b) SdHO amplitude for different θ, as marked, normalized to their values at $\theta = 0$, as a function of ϵ and filling factor ν, respectively. It is clear that the decay of the MIRO amplitude is most pronounced at lower ϵ (*higher* $B_\parallel$) [cf. Eq. (2)] and at the highest tilt angle, in agreement with Eqs. (1),(2). The SdHO decay, on the other hand, shows a very different behavior. Indeed, at all tilt angles studied, the SdHO amplitude appears to be damped rather uniformly, i.e., the degree of suppression is roughly independent of the filling factor (and, hence, of $B_\parallel$).

We notice, however, that the SdHO data are confined to a rather narrow range of perpendicular magnetic fields (1.7 kG $\le B_\perp \le$ 2 kG), in contrast to MIRO which are studied

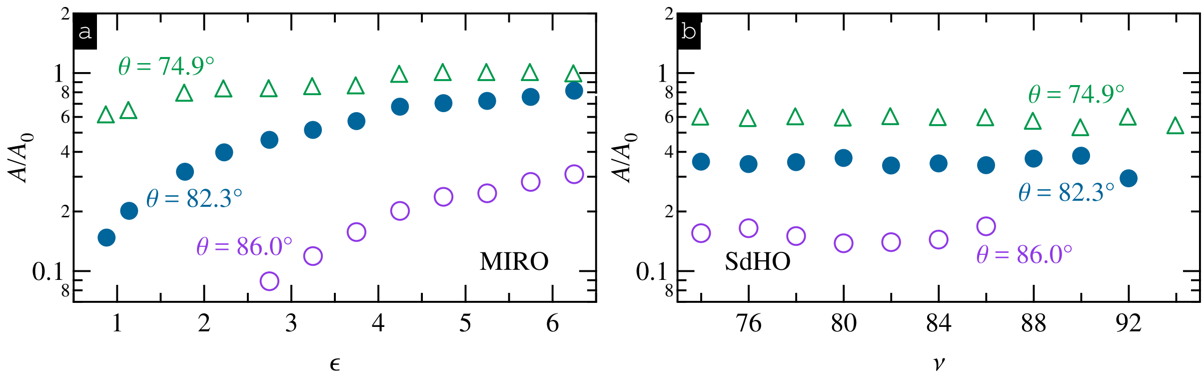

Figure 4. (a) MIRO amplitude and (b) SdHO amplitude for different θ, as marked, normalized to its value at $\theta = 0$, as a function of ϵ and filling factor ν, respectively.

over a much wider range (0.2 kG $\leq B_\perp \leq$ 1 kG). This fact clearly limits our ability to detect possible dependence on ν from the data presented in Fig. 4(b). In addition, the SdHO range of $B_\perp$ definitely falls into the regime of well separated Landau levels, where the density of states can no longer be described by a single harmonic with the amplitude given by the Dingle factor. As a result, in order to see if the modification of the quantum lifetime can account for the observed SdHO suppression, the theoretical description of the SdHO should first be extended to the regime of separated Landau levels.

Finally, we notice that in a recent study [51], the reduced SdHO amplitude in tilted magnetic fields was attributed to a $B_\parallel$-induced increase of the spin splitting. In another report [52], however, the SdHO were not suppressed until much higher tilt angles (and higher $B_\parallel$) than those used in the present study, suggesting that the effect might be sample dependent.

4. Summary

In summary, we have compared the effects of an in-plane magnetic field on MIRO and on SdHO in a high-mobility 2DEG. The decay of the MIRO amplitude with increasing tilt angle can be understood in terms of a $B_\parallel$-induced increase of the single particle scattering rate which acquires a quadratic-in-$B_\parallel$ correction. The decay of SdHO, on the other hand, shows a uniform suppression at all filling factors studied. However, because of the limited range of $B_\perp$ and the fact that SdHO appears in the regime of separated Landau levels, further investigations are needed to identify the origin of the SdHO suppression.

5. Acknowledgments

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References

[1] Zudov M A, Du R R, Simmons J A and Reno J L 2001 *Phys. Rev. B* **64** 201311(R)
[2] Ye P D, Engel L W, Tsui D C, Simmons J A, Wendt J R, Vawter G A and Reno J L 2001 *Appl. Phys. Lett.* **79** 2193
[3] Zudov M A, Ponomarev I V, Efros A L, Du R R, Simmons J A and Reno J L 2001 *Phys. Rev. Lett.* **86** 3614
[4] Yang C L, Zhang J, Du R R, Simmons J A and Reno J L 2002 *Phys. Rev. Lett.* **89** 076801
[5] Mani R G, Smet J H, von Klitzing K, Narayanamurti V, Johnson W B and Umansky V 2002 *Nature (London)* **420** 646
[6] Zudov M A, Du R R, Pfeiffer L N and West K W 2003 *Phys. Rev. Lett.* **90** 046807

[7] Kukushkin I V, Akimov M Y, Smet J H, Mikhailov S A, von Klitzing K, Aleiner I L and Falko V I 2004 *Phys. Rev. Lett.* **92** 236803
[8] Zhang W, Zudov M A, Pfeiffer L N and West K W 2007 *Phys. Rev. Lett.* **98** 106804
[9] Zhang W, Zudov M A, Pfeiffer L N and West K W 2008 *Phys. Rev. Lett.* **100** 036805
[10] Khodas M, Chiang H S, Hatke A T, Zudov M A, Vavilov M G, Pfeiffer L N and West K W 2010 *Phys. Rev. Lett.* **104** 206801
[11] Wiedmann S, Gusev G M, Raichev O E, Bakarov A K and Portal J C 2010 *Phys. Rev. Lett.* **105** 026804
[12] Hatke A T, Chiang H S, Zudov M A, Pfeiffer L N and West K W 2010 *Phys. Rev. B* **82** 041304(R)
[13] Dai Y, Du R R, Pfeiffer L N and West K W 2010 *Phys. Rev. Lett.* **105** 246802
[14] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2011 *Phys. Rev. B* **83** 121301(R)
[15] Andreev A V, Aleiner I L and Millis A J 2003 *Phys. Rev. Lett.* **91** 056803
[16] Durst A C, Sachdev S, Read N and Girvin S M 2003 *Phys. Rev. Lett.* **91** 086803
[17] Lei X L and Liu S Y 2003 *Phys. Rev. Lett.* **91** 226805
[18] Vavilov M G and Aleiner I L 2004 *Phys. Rev. B* **69** 035303
[19] Dmitriev I A, Mirlin A D and Polyakov D G 2003 *Phys. Rev. Lett.* **91** 226802
[20] Dmitriev I A, Vavilov M G, Aleiner I L, Mirlin A D and Polyakov D G 2005 *Phys. Rev. B* **71** 115316
[21] Khodas M and Vavilov M G 2008 *Phys. Rev. B* **78** 245319
[22] Dmitriev I A, Khodas M, Mirlin A D, Polyakov D G and Vavilov M G 2009 *Phys. Rev. B* **80** 165327
[23] Hatke A T, Khodas M, Zudov M A, Pfeiffer L N and West K W 2011 *Phys. Rev. B* **84** 241302(R)
[24] Zudov M A 2004 *Phys. Rev. B* **69** 041304(R)
[25] Willett R L, Pfeiffer L N and West K W 2004 *Phys. Rev. Lett.* **93** 026804
[26] Studenikin S A, Potemski M, Coleridge P T, Sachrajda A S and Wasilewski Z R 2004 *Solid State Commun.* **129** 341
[27] Studenikin S A, Potemski M, Sachrajda A, Hilke M, Pfeiffer L N and West K W 2005 *Phys. Rev. B* **71** 245313
[28] Smet J H, Gorshunov B, Jiang C, Pfeiffer L, West K, Umansky V, Dressel M, Meisels R, Kuchar F and von Klitzing K 2005 *Phys. Rev. Lett.* **95** 116804
[29] Zudov M A, Du R R, Pfeiffer L N and West K W 2006 *Phys. Rev. B* **73** 041303(R)
[30] Zudov M A, Du R R, Pfeiffer L N and West K W 2006 *Phys. Rev. Lett.* **96** 236804
[31] Bykov A A, Bakarov A K, Islamov D R and Toropov A I 2006 *JETP Lett.* **84** 391
[32] Studenikin S A, Sachrajda A S, Gupta J A, Wasilewski Z R, Fedorych O M, Byszewski M, Maude D K, Potemski M, Hilke M, West K W and Pfeiffer L N 2007 *Phys. Rev. B* **76** 165321
[33] Hatke A T, Chiang H S, Zudov M A, Pfeiffer L N and West K W 2008 *Phys. Rev. B* **77** 201304(R)
[34] Hatke A T, Chiang H S, Zudov M A, Pfeiffer L N and West K W 2008 *Phys. Rev. Lett.* **101** 246811
[35] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2009 *Phys. Rev. Lett.* **102** 066804
[36] Bykov A A, Marchishin I V, Goran A V and Dmitriev D V 2010 *Appl. Phys. Lett.* **97** 082107
[37] Dorozhkin S I, Pfeiffer L, West K, von Klitzing K and Smet J H 2011 *Nature Phys.* **7** 336
[38] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2011 *Phys. Rev. B* **83** 201301(R)
[39] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2011 *Phys. Rev. B* **84** 241304(R)
[40] Hatke A T, Zudov M A, Watson J D and Manfra M J 2012 *Phys. Rev. B* **85** 121306(R)
[41] Hatke A T, Zudov M A, Watson J D, Manfra M J, Pfeiffer L N and West K W 2012 *unpublished*
[42] Dmitriev I A, Mirlin A D, Polyakov D G and Zudov M A 2012 *Rev. Mod. Phys.* **84** 1709
[43] Pioro-Ladrière M, Abolfath M R, Zawadzki P, Lapointe J, Studenikin S A, Sachrajda A S and Hawrylak P 2005 *Phys. Rev. B* **72** 125307
[44] Mani R G 2005 *Phys. Rev. B* **72** 075327
[45] Yang C L, Du R R, Pfeiffer L N and West K W 2006 *Phys. Rev. B* **74** 045315
[46] Bogan A, Hatke A T, Studenikin S A, Sachrajda A, Zudov M A, Pfeiffer L N and West K W 2012 *Phys. Rev. B* **86** 235305
[47] Zhang W, Chiang H S, Zudov M A, Pfeiffer L N and West K W 2007 *Phys. Rev. B* **75** 041304(R)
[48] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2009 *Phys. Rev. B* **79** 161308(R)
[49] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2011 *Phys. Rev. B* **83** 081301(R)
[50] Elzerman J M, Hanson R, Beveren L H W v, Witkamp B, Vandersypen L M K and Kouwenhoven L P 2004 *Nature* **430** 431
[51] Romero N, McHugh S, Sarachik M P, Vitkalov S A and Bykov A A 2008 *Phys. Rev. B* **78** 153311
[52] Hatke A T, Zudov M A, Pfeiffer L N and West K W 2012 *Phys. Rev. B* **85** 241305(R)