RAPID COMMUNICATIONS

PHYSICAL REVIEW B **85**, 121306(R) (2012)

Magnetoplasmon resonance in a two-dimensional electron system driven into a zero-resistance state

A. T. Hatke,[1] M. A. Zudov,[1,*] J. D. Watson,[2,3] and M. J. Manfra[2,3]

[1]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

[2]*Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA*

[3]*Birck Nanotechnology Center, School of Materials Engineering and School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*

(Received 12 January 2012; published 30 March 2012)

We report on a very strong, and a rather sharp, photoresistance peak originating from a dimensional magnetoplasmon resonance (MPR) in a high-mobility GaAs/AlGaAs quantum well driven by microwave radiation into a zero-resistance state (ZRS). The analysis of the MPR signal reveals a negative background, providing experimental evidence for the concept of absolute negative resistance associated with the ZRS. When the system is further subject to a dc field, the maxima of microwave-induced resistance oscillations decay away and the system reveals a state with close-to-zero differential resistance. The MPR peak, on the other hand, remains essentially unchanged, indicating robust Ohmic behavior under the MPR conditions.

DOI: 10.1103/PhysRevB.85.121306 PACS number(s): 73.43.Qt, 73.63.Hs, 73.40.−c

Recent low-field magnetotransport experiments in very-high-mobility two-dimensional electron systems (2DESs) revealed a variety of remarkable phenomena,[1–9] which include microwave-induced resistance oscillations (MIROs).[1,10–13] MIROs originate from either the *displacement* mechanism,[14–18] stepping from the modification of impurity scattering by microwaves, or from the *inelastic* mechanism,[18,19] owing to the radiation-induced nonequilibrium distribution of electrons. In either case, MIROs can be described by a radiation-induced correction (photoresistivity) of the form

$$\delta\rho_\omega \propto -\sin(2\pi\omega/\omega_c), \quad (1)$$

where $\omega_c = eB/m^\star$ is the cyclotron frequency, $m^\star$ is the electron effective mass, and $\omega = 2\pi f$ is the microwave frequency. The negative photoresistance at the MIRO minima can approach (but cannot exceed) the dark resistivity, by absolute value, giving rise to zero-resistance states (ZRSs).[4,5,20–25] It was predicted theoretically[26] that ZRSs emerge as a result of an instability of the underlying negative resistance.

In addition to MIROs, microwave photoresistance can also reveal magnetoplasmon resonance (MPR).[1,27–32] The dispersion of 2D plasmons in the long-wavelength limit was calculated by Stern,[33]

$$\omega_p^2(q) = \frac{e^2 n_e}{2\varepsilon_0 \bar{\varepsilon} m^*} q, \quad (2)$$

where ε_0 is the permittivity of vacuum, $\bar{\varepsilon}$ is the effective dielectric constant of the surroundings,[34] and n_e is the density of 2D electrons. In a laterally confined 2DES, such as a long Hall bar of width w, the fundamental mode of standing plasmon oscillations has a wave number $q_0 = \pi/w$. Upon application of a perpendicular magnetic field B, the plasmon mode hybridizes with the cyclotron resonance[35] and the dispersion of a combined (magnetoplasmon) mode is given by

$$\omega^2 = \omega_c^2 + \omega_p^2. \quad (3)$$

In contrast to MIROs, there exists no theory of MPR photoresistance. However, it is believed that radiation absorption translates to electron heating which, in turn, causes a (usually positive[36]) resistivity change.[27,28]

While both MPR and MIROs were realized simultaneously in several experiments,[1,29–31,37] the MPR peak remained much smaller than both MIROs and the dark resistivity. Moreover, even in studies using ultrahigh-mobility 2DES, the MPR peak remained weak but was broad enough to completely destroy the ZRS.[29] On the other hand, it is interesting to see if the MPR can be used to study ZRSs and, e.g., to obtain information on the underlying absolute negative resistance predicted almost a decade ago.[26] Furthermore, there exist no studies of the MPR in strong dc electric fields, which were successfully used to get insight into other low-field phenomena.[38–41]

In this Rapid Communication, we report on microwave photoresistivity measurements in a high-mobility 2DES. In addition to MIROs and ZRSs, our experiment reveals a remarkably strong and sharp photoresistance peak. This peak originates from a dimensional MPR and, in contrast to previous studies, its height is comparable to the MIRO amplitude, to the zero-field resistivity, and is several times larger than the dark resistivity. By tuning the microwave frequency, the MPR and ZRS conditions can be satisfied simultaneously, giving rise to a reentrant ZRS interrupted by the sharp MPR peak. A Lorentzian fit of the MPR peak reveals a negative background, providing strong evidence for the absolute negative resistance associated with ZRSs.[26] Upon application of a dc electric field, low-order MIRO maxima quickly decay and the 2DES goes into a state with close-to-zero differential resistance.[42] The MPR peak, on the other hand, shows surprisingly little sensitivity to the dc field, both in its magnitude and in its position. This behavior implies that under the MPR condition, the resistivity remains Ohmic to much larger currents compared to both MIROs and the dark resistivity.

Our sample is a lithographically defined Hall bar (width $w = 50$ μm) fabricated from a 300-Å-wide GaAs/$Al_{0.24}Ga_{0.76}As$ quantum well grown by molecular beam epitaxy. After a brief low-temperature illumination, the density and the mobility were $n_e \approx 2.9 \times 10^{11}$ cm^{-2} and $\mu \simeq 1.3 \times 10^7$ cm^2/V s, respectively. Microwave radiation of frequency f, generated by a backward wave oscillator, was delivered to the sample via a 1/4-in.- (6.35-mm-) diameter light pipe. The resistivity ρ_ω and the differential resistivity $r_\omega \equiv dV/dI$ were measured using a low-frequency lock-in technique

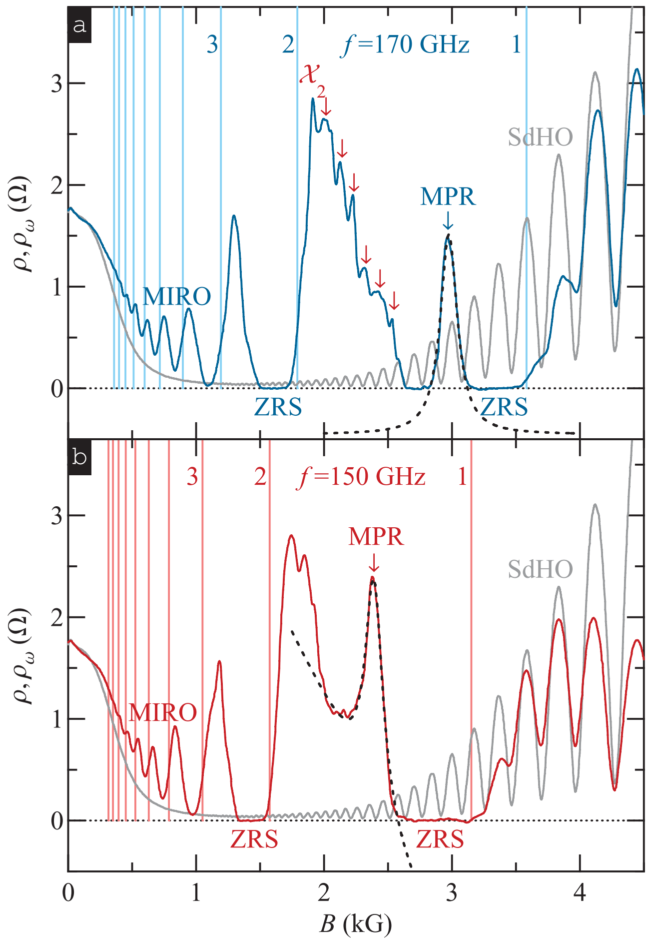

FIG. 1. (Color online) Magnetoresistivity $\rho_\omega(B)$ (Ref. 43) (dark curves) under microwave irradiation of frequency (a) $f = 170$ GHz and (b) $f = 150$ GHz at $T = 0.65$ K. Both panels also show $\rho(B)$ measured without irradiation (light curves). The dashed curves are fits to the data (see text). The vertical lines are drawn at the harmonics of the cyclotron resonance, $\omega/\omega_c = 1,2,3,\ldots$, obtained from the MIRO period. The MPR and $\mathcal{X}_2$ peaks are marked by "MPR" and by "$\mathcal{X}_2$," respectively. Arrows mark an additional series of peaks.

under continuous microwave irradiation in sweeping magnetic field.

In Figs. 1(a) and 1(b) we present resistivity ρ_ω (dark curves) as a function of magnetic field B under microwave irradiation of frequency $f = 170$ GHz and $f = 150$ GHz, respectively, measured at $T = 0.65$ K. For comparison, both panels also show magnetoresistivity $\rho(B)$ measured without microwave irradiation (light curves). Without radiation, $\rho(B)$ exhibits a strong negative magnetoresistance effect[44–47] followed by Shubnikov–de Haas oscillations at $B \gtrsim 1.5$ kG. Under microwave irradiation, the magnetoresistivity $\rho_\omega(B)$ reveals pronounced MIROs which persist up to the tenth order. Being controlled by ω/ω_c [cf. Eq. (1)], MIROs appear near the cyclotron resonance harmonics at both frequencies (cf. vertical lines drawn at $\omega/\omega_c = 1,2,3,\ldots$). We further notice that $\rho_\omega(B)$ reveals a series of fast oscillations superimposed on the second MIRO maximum [cf. ↓ in Fig. 1(a)]. At this point we are not certain about the origin of these oscillations[48] but the position and the shape of the maximum closest to the second cyclotron resonance harmonic [marked by "$\mathcal{X}_2$" in Fig. 1(a)] appear consistent with the recently discovered $\mathcal{X}_2$ peak,[41,44,45,49,50] whose nature, however, is also unknown.

Further examination of the data reveals that the lower-order MIRO minima are developed into ZRSs, attesting to the high quality of our 2DES. Remarkably, the fundamental (first-order) ZRS in Fig. 1(a) is interrupted by a very strong and sharp photoresistance peak. As we show below, this peak (marked by "MPR") corresponds to the fundamental mode of the dimensional MPR, which apparently can easily destroy the current domain structure associated with the ZRS.[25,26] The height of this MPR peak in our experiment is *several times larger* than the dark resistivity. This finding contrasts with previous studies,[1,27–29] where the the MPR photoresistance was only a few percent of the dark resistivity. While the origin of such a giant response to MPR in our 2DES is not precisely known, it might be qualitatively explained by strong temperature dependence[47] of the dark resistivity in the regime of the giant negative magnetoresistance.[44–47] Under the MPR condition, this strong temperature dependence translates to a giant resistivity peak owing to electron heating due to resonant absorption of radiation.

We next examine the height, the position, and the width of the MPR peak shown in Fig. 1(a) in more detail. The peak height, if measured from zero, is about 1.5 Ω, which is comparable to both the zero-field resistivity and the third-order MIRO peak. However, since the MPR peak is overlapping with the ZRS, which is believed to be characterized by an underlying negative resistance,[23,26] the actual height of the peak should be even larger. To test this prediction, and to obtain other characteristics of the MPR photoresistance, we fit our data with the Lorentzian, $\rho_\omega(B) = a + b/[(B - B_0)^2 + (\delta B)^2]$, and present the result as a dashed curve in Fig. 1(a). The fitting procedure reveals the negative background $a \approx -0.45$ Ω,[51] suggesting that the actual height of the MPR peak in Fig. 1(a) is close to 2.0 Ω, and that the MPR photoresistance can be used to probe the absolute negative resistance associated with the ZRS.[52] We also notice that the half-width of the MPR peak, $\delta B \approx 0.08$ kG ≈ 0.16 K, is considerably smaller than the radiative decay rate $\tau_{\rm em}^{-1} = n_e e^2/2\epsilon_0\sqrt{\bar\varepsilon} m^\star c$, $\sqrt{\bar\varepsilon} = (\sqrt{12.8} + 1)/2 \approx 2.3$,[53] which we estimate as $\tau_{\rm em}^{-1} \approx 0.74$ K in our 2DES.

With $B_0 \approx 3.0$ kG and $m^\star = 0.067 m_0$, we calculate the plasmon frequency $f_p = \sqrt{\omega^2 - \omega_c^2}/2\pi \approx 115$ GHz using Eq. (3). This value is somewhat lower than $\omega_p(q_0)/2\pi \approx 126$ GHz obtained from Eq. (2). We notice that the dispersion given by Eq. (3) is generally valid in a quasielectrostatic approximation where the retardation effects can be ignored.[54,55] According to Ref. 55, the importance of retardation can be described by the ratio of the plasmon frequency to the frequency of light with the same wave vector, $\alpha = \sqrt{e^2 n_e w/2\pi \varepsilon_0 m^\star c^2}$. In our Hall bar, we estimate $\alpha \simeq 0.15$ and thus do not expect significant modification of the MPR dispersion. It is known, however, that even when retardation effects are not important, the actual plasmon frequency is expected to be about 15% lower than $\omega_p(q_0)$ estimated from Eq. (2).[54,55] Such a reduction was observed in both early[27] and more recent[28,37] experiments.

As shown in Fig. 1(b), at $f = 150$ GHz the MPR peak is moved toward the second MIRO maximum and is no longer overlapping with the ZRS. This observation is consistent with the MPR dispersion relation, Eq. (3), which dictates

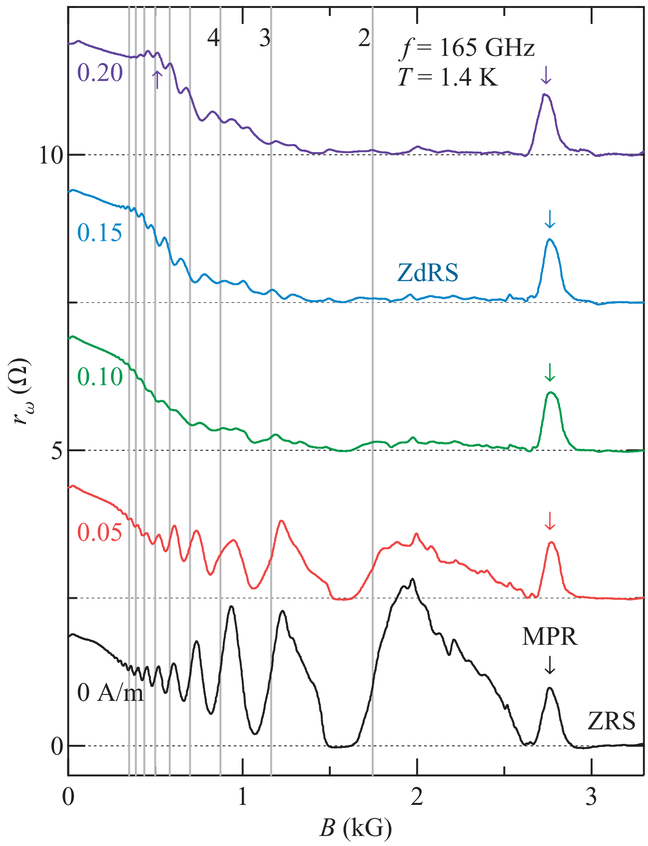

FIG. 2. (Color online) Differential resistivity r_ω vs magnetic field B under microwave irradiation of $f = 165$ GHz measured at $T = 1.4$ K for different current densities from $j = 0$ to 0.20 A/m, in a step of 0.05 A/m. The traces are vertically offset for clarity by 2.5 Ω. The vertical lines are drawn at the harmonics of the cyclotron resonance, $\omega/\omega_c = 1,2,3,\ldots$.

stronger, compared to MIRO, dependence of the MPR peak position on the microwave frequency. Direct comparison of the data at $f = 170$ GHz and at $f = 150$ GHz reveals roughly equal MIRO amplitudes, indicative of comparable effective microwave intensities incident on our 2DES. We fit our data (cf. dashed curve) in the vicinity of the MPR peak with $\rho_\omega(B) = a + b/[(B - B_0)^2 + (\delta B)^2] + c(B - B_0)$, where the last term accounts for a B-dependent background. Unlike the $f = 170$ GHz data, the fit reveals positive background resistance, $a \approx 0.15$ Ω, explaining a considerably higher (≈2.35 Ω if measured from zero) MPR peak compared to the one at $f = 170$ GHz.

We now turn to the role of a dc electric field on MIROs and, especially, on the MPR peak. In Fig. 2 we present the differential resistivity r_ω as a function of B measured at $T = 1.4$ K, under microwave irradiation of $f = 165$ GHz, and selected direct current densities from $j \equiv I/w = 0$ to 0.20 A/m, in a step of 0.05 A/m. The traces are vertically offset for clarity by 2.5 Ω and the vertical lines are drawn at the harmonics of the cyclotron resonance, $\omega/\omega_c = 1,2,3,\ldots$. First, we observe that the response of MIROs to the dc field is strongly nonlinear. Indeed, already at $j = 0.05$ A/m ($I = 2.5$ μA) MIROs decrease in amplitude by about a factor of 2 and at $j = 0.10$ A/m almost disappear. At higher j, high-order MIROs reappear and start shifting toward higher B, in agreement with previous experimental[38,39,41] and theoretical[56,57] studies. This behavior is a result of nonlinear mixing of MIROs and Hall field-induced resistance oscillations,[3,58–60] arising due to electron backscattering off short-range disorder between Hall field tilted Landau levels. On the other hand, the low-order MIRO maxima remain strongly suppressed and the data reveal a state with close-to-zero differential resistance which spans a wide magnetic field range. The presence of microwave irradiation in formation of these states is not essential since they also emerge in a nonirradiated 2DES in a similar range of electric and magnetic fields.[42]

Unlike MIROs, which change dramatically with increasing dc field, the MPR peak shows surprisingly little variation both in magnitude and in position. This behavior is totally unexpected since it demonstrates that the microwave radiation protects Ohmic behavior within a narrow magnetic field range corresponding to the MPR. We note that in all previous experiments within this range of dc fields, both with and without microwave radiation, the Ohmic regime always remained limited to an order of magnitude lower magnetic fields.[38,42,58]

In summary, we have studied microwave photoresistance of a Hall bar-shaped, high-mobility GaAs/AlGaAs quantum well. In addition to microwave-induced resistance oscillations and zero-resistance states, the photoresistance reveals a distinct peak which originates from a fundamental mode of a dimensional magnetoplasmon resonance. This MPR peak is several times higher than the dark resistivity, likely due to strongly temperature-dependent dark resistivity[47] in our 2DES. Analysis of the MPR peak, when it is superimposed onto a ZRS, allows us to obtain information about the ZRS-associated absolute negative resistance, which is otherwise masked by instabilities.[26] When the irradiated system is further subject to a dc electric field, microwave-induced resistance oscillations quickly decay and the 2DES exhibits a state with close-to-zero differential resistance. The MPR peak, on the other hand, is found to be immune to the dc field exhibiting Ohmic behavior.

We thank J. Jaroszynski, J. Krzystek, 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.

*Corresponding author: zudov@physics.umn.edu

[1] M. A. Zudov, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. B **64**, 201311(R) (2001).

[2] M. A. Zudov, I. V. Ponomarev, A. L. Efros, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **86**, 3614 (2001).

[3] C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002).

[4] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, W. B. Johnson *et al.*, Nature (London) **420**, 646 (2002).

[5]M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **90**, 046807 (2003).
[6]C. L. Yang, M. A. Zudov, T. A. Knuuttila, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **91**, 096803 (2003).
[7]I. V. Kukushkin, M. Y. Akimov, J. H. Smet, S. A. Mikhailov, K. von Klitzing, I. L. Aleiner, and V. I. Falko, Phys. Rev. Lett. **92**, 236803 (2004).
[8]A. A. Bykov, J.-Q. Zhang, S. Vitkalov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. Lett. **99**, 116801 (2007).
[9]M. Khodas, H. S. Chiang, A. T. Hatke, M. A. Zudov, M. G. Vavilov, and L. N. Pfeiffer, Phys. Rev. Lett. **104**, 206801 (2010).
[10]S. A. Studenikin, M. Potemski, A. Sachrajda, M. Hilke, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **71**, 245313 (2005).
[11]S. A. Studenikin, A. S. Sachrajda, J. A. Gupta, Z. R. Wasilewski, O. M. Fedorych *et al.*, Phys. Rev. B **76**, 165321 (2007).
[12]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **102**, 066804 (2009).
[13]A. T. Hatke, M. Khodas, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **84**, 241302(R) (2011).
[14]V. I. Ryzhii, Sov. Phys. Solid State **11**, 2078 (1970).
[15]A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. **91**, 086803 (2003).
[16]X. L. Lei and S. Y. Liu, Phys. Rev. Lett. **91**, 226805 (2003).
[17]M. G. Vavilov and I. L. Aleiner, Phys. Rev. B **69**, 035303 (2004).
[18]I. A. Dmitriev, M. Khodas, A. D. Mirlin, D. G. Polyakov, and M. G. Vavilov, Phys. Rev. B **80**, 165327 (2009).
[19]I. A. Dmitriev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B **71**, 115316 (2005).
[20]R. L. Willett, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **93**, 026804 (2004).
[21]J. H. Smet, B. Gorshunov, C. Jiang, L. Pfeiffer, K. West, V. Umansky, M. Dressel, R. Meisels, F. Kuchar, and K. von Klitzing, Phys. Rev. Lett. **95**, 116804 (2005).
[22]M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **73**, 041303(R) (2006).
[23]M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **96**, 236804 (2006).
[24]A. A. Bykov, A. K. Bakarov, D. R. Islamov, and A. I. Toropov, JETP Lett. **84**, 391 (2006).
[25]S. I. Dorozhkin, L. Pfeiffer, K. West, K. von Klitzing, and J. H. Smet, Nat. Phys. **7**, 336 (2011).
[26]A. V. Andreev, I. L. Aleiner, and A. J. Millis, Phys. Rev. Lett. **91**, 056803 (2003).
[27]E. Vasiliadou, G. Miller, D. Heitmann, D. Weiss, K. von Klitzing *et al.*, Phys. Rev. B **48**, 17145 (1993).
[28]I. V. Kukushkin, V. M. Muravev, J. H. Smet, M. Hauser, W. Dietsche *et al.*, Phys. Rev. B **73**, 113310 (2006).
[29]C. L. Yang, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **74**, 045315 (2006).
[30]S. I. Dorozhkin, J. H. Smet, K. von Klitzing, L. N. Pfeiffer, and K. W. West, JETP Lett. **86**, 543 (2007).
[31]L.-C. Tung, C. L. Yang, D. Smirnov, L. N. Pfeiffer, K. W. West *et al.*, Solid State Commun. **149**, 1531 (2009).
[32]I. V. Andreev, V. M. Muravev, I. V. Kukushkin, S. Schmult, and W. Dietsche, Phys. Rev. B **83**, 121308(R) (2011).
[33]F. Stern, Phys. Rev. Lett. **18**, 546 (1967).
[34]In our 2DES, $\bar{\varepsilon} \approx 6.9$, which is the average of dielectric constant of GaAs (12.8) and that of free space (1).
[35]A. V. Chaplik, Sov. Phys. JETP **35**, 395 (1972).
[36]A negative MPR photoresistance was reported in Ref. 31.
[37]Z. Q. Yuan, C. L. Yang, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **74**, 075313 (2006); A. A. Bykov, JETP Lett. **87**, 551 (2008).
[38]W. Zhang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **98**, 106804 (2007).
[39]A. T. Hatke, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **77**, 201304(R) (2008).
[40]A. T. Hatke, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **101**, 246811 (2008).
[41]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 201301(R) (2011).
[42]A. T. Hatke, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **82**, 041304(R) (2010).
[43]Measured at $B < 0$, negative magnetoresistance, MIROs, and the MPR photoresistance peak are all of approximately the same strength as their counterparts at $B > 0$.
[44]Y. Dai, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **105**, 246802 (2010).
[45]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 121301(R) (2011).
[46]L. Bockhorn, P. Barthold, D. Schuh, W. Wegscheider, and R. J. Haug, Phys. Rev. B **83**, 113301 (2011).
[47]A. T. Hatke, M. A. Zudov, J. L. Reno, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **85**, 081304 (2012).
[48]As an origin for these oscillations one can consider, e.g., a radiation-induced modification of the Shubnikov–de Haas oscillations, see I. A. Dmitriev, J. Phys.: Conf. Ser. **334**, 012015 (2011).
[49]Y. Dai, K. Stone, I. Knez, C. Zhang, R. R. Du, C. Yang, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **84**, 241303 (2011).
[50]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **84**, 241304(R) (2011).
[51]Reducing the fitting range results in up to ≈20% larger values of $|a|$.
[52]Information on negative resistance can also be obtained from bichromatic microwave photoresistance (Ref. 23).
[53]K. W. Chiu, T. K. Lee, and J. J. Quinn, Surf. Sci. **58**, 182 (1976).
[54]S. A. Mikhailov, Phys. Rev. B **70**, 165311 (2004).
[55]S. A. Mikhailov and N. A. Savostianova, Phys. Rev. B **71**, 035320 (2005).
[56]X. L. Lei, Appl. Phys. Lett. **91**, 112104 (2007).
[57]M. Khodas and M. G. Vavilov, Phys. Rev. B **78**, 245319 (2008).
[58]W. Zhang, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **75**, 041304(R) (2007).
[59]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **79**, 161308(R) (2009).
[60]A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 081301(R) (2011).