Effect of rotation of the polarization of linearly polarized microwaves on the radiation-induced magnetoresistance oscillations

A. N. Ramanayaka,¹ R. G. Mani,¹ J. Iñarrea,² and W. Wegscheider³

¹Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303
²Escuela Politécnica Superior, Universidad Carlos III, Leganes, Madrid, 28911, Spain
³Laboratorium für Festkörperphysik, ETH Zürich, 8093 Zürich, Switzerland

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Light-matter coupling is investigated by rotating, by an angle θ, the polarization of linearly polarized microwaves with respect to the long-axis of GaAs/AlGaAs Hall-bar electron devices. At low microwave power, $P$, experiments show a strong sinusoidal variation in the diagonal resistance $R_{xx}$ vs. $θ$ at the oscillatory extrema, indicating a linear polarization sensitivity in the microwave radiation-induced magnetoresistance oscillations. Surprisingly, the phase shift $θ_{0}$ for maximal oscillatory $R_{xx}$ response under photoexcitation appears dependent upon the radiation-frequency $f$, the extremum in question, and the magnetic field orientation or $\text{sgn}(B)$.

INTRODUCTION

Vanishing electrical resistance has long been viewed as a harbinger of new physics in condensed matter since the discovery of superconductivity.[1] Transport studies of two-dimensional electron systems (2DES) supported this notion by revealing the quantum Hall effects as correlates of vanishing diagonal resistance at low temperatures, $T$, and high magnetic fields, $B$.[2] In the recent past, low-$B$ transport studies under microwave irradiation in the 2DES uncovered the possibility of eliminating backscattering by photo-excitation, without concurrent Hall quantization.[3, 4] The experimental realization of such radiation-induced zero-resistance states, and associated $B^{-1}$-periodic radiation-induced magnetoresistance oscillations expanded the experimental[3–15, 17–21] and theoretical[22–37] investigations of light-matter coupling in low-dimensional electronic systems. Indeed, microwave excitation of semiconductor quantum wells and graphene ribbons is now viewed as an approach to artificially realizing a (Floquet) topological insulator for possible applications in topological quantum computing and spintronics.[36–39]

Microwave-induced zero-resistance states appear when the associated $B^{-1}$-periodic magnetoresistance oscillations grow in amplitude and become comparable to the dark resistance of the 2DES. Such oscillations, which exhibit nodes at cyclotron resonance and harmonics thereof,[3, 5] are now understood via the displacement model,[22, 24, 26, 33] the non-parabolicity model,[25] the inelastic model,[27] and the radiation driven electron orbit model.[28–30] Recently, a magneto-plasmon approach has also been motivated.[35] In theory, some of these mechanisms can drive the magnetoresistivity to negative values at the oscillatory minima. Negative resistivity then triggers an instability in favor of current domain formation, and zero-resistance states.[23, 32]

A distinguishing feature between existing theories for the radiation-induced oscillating magnetoresistivity concerns the role of the microwave-polarization. Here, the displacement model predicts that the oscillation-amplitude depends on whether the linearly polarized microwave electric field, $E_{ω}$, is parallel or perpendicular to the dc-electric field, $E_{DC}$.[24] More specifically,[24], the inter-Landau level contribution to the photo-current in this theory includes a term with a Bessel function whose argument depends upon whether $E_{DC}$ and $E_{ω}$ are parallel or perpendicular to each other, and this Bessel-function-argument is a constant for circular polarized or unpolarized radiation for any ratio of $ω_{c}/ω$.[24] In contrast, the inelastic model suggests insensitivity of the photoconductivity to the polarization orientation of the linearly polarized microwave field.[27] The radiation-driven electron orbit model indicates a polarization immunity that depends upon the damping factor, $γ$, a material- and sample-dependent parameter, exceeding the microwave angular frequency, $ω$.[29, 30] Finally, within the non-parabolicity model, the effect of irradiation on dc transport emerges only for linear-, but not circular-, polarization of the radiation field.[25] Consequently, the radiation induced contribution within this theory depends on the relative orientation between $E_{DC}$ and the linearly polarized $E_{ω}$.[25]

The polarization aspect has been explored by experiment in ref.[9, 14], and [21]. Measurements carried out on L-shaped specimens have suggested that the period and phase of the radiation induced magnetoresistance oscillations are the same for the $E_{ω} \parallel I$ and $E_{ω} \perp I$ configurations.[9] Ref.[14] has reported the immunity of microwave-induced magneto-resistance oscillations and zero resistance states to the sense of circular- and linear-polarizations from the experiments carried out on specimens with a square geometry in a quasioptical setup. In a recent study, Mani et al. [21] reported a strong sensitivity in the amplitude of the radiation-induced magneto-resistance oscillations to the relative orientation of the linear polarization with respect to the Hall bar axis.

Here, we examine the effect of rotating the polarization
of linearly polarized microwaves on the radiation-induced magnetoresistance oscillations in the GaAs/AlGaAs 2D electron system.[21] Surprisingly, at low microwave power, $P$, experiments indicate a strong sinusoidal response as $R_{xx}(\theta) = A + C \cos^2(\theta - \theta_0)$ vs. the polarization rotation angle, $\theta$, with the $'+'$ and $'-'$ cases describing the maxima and minima, respectively. At higher $P$, the principal resistance minimum exhibits additional extrema vs. $\theta$. Notably, the phase shift $\theta_0$ can vary with $f$, $B$, and $\text{sgn}(B)$.

EXPERIMENT AND RESULTS

These polarization-dependence studies utilized the novel setup illustrated in Fig. 1(a). Here, a rotatable MW-antenna introduces microwaves into a 11 mm diameter circular waveguide. The circular symmetry then allows the rotation of the antenna and the polarization with respect to the stationary sample, see Fig. 1(a) and 1(b). Note that the transverse electric (TE) mode is excited by the microwave (MW) antenna of Fig. 1(a), and the specimen is subject to the $TE_{11}$ mode of the circular waveguide as shown in Fig. 1(c). These scaled sketches of the small (0.4 mm wide) Hall bar sample within the 11 mm i.d. waveguide, with superimposed electric field lines (see Fig. 1(c)), suggest a well defined polarization over the active area of the specimen, for all rotation angles. The samples consisted of 400 $\mu$m-wide Hall bars characterized by $n \approx 400$ $\text{cm}^{-2}$ and $\mu \approx 8 \times 10^6 \text{cm}^2/\text{V}s$. The long axis of these Hall bars were visually aligned parallel to the polarization axis of the MW-antenna for the data exhibited in Fig. 1 - 4, and this defined $\theta = 0^\circ$. Thus, $\theta$, see Fig. 1(b) and Fig. 1(c) represents the polarization rotation angle. Note that, for the measurements exhibited in Fig. 5, however, the Hall bar was oriented perpendicular to the MW-antenna at the outset, i.e., at $\theta = -90^\circ$.

Tests of this setup utilized also an “analyzer” consisting of a probe-coupled antenna and a square law detector. Measurements carried out with the MW-antenna (Fig. 1(a)) connected directly to the analyzer indicated that polarized microwaves were generated by the MW-antenna. In the next step, the waveguide sample holder was inserted between the polarizer (MW-antenna) and the analyzer. Here, the analyzer was fixed at a particular orientation, and the MW-antenna was rotated over $360^\circ$. Fig. 1(d) shows the normalized detector response, $V_D$, at $f = 40 \text{GHz}$. Figure 1(d) exhibits the expected sinusoidal variation, i.e., $V_D \propto \cos^2 \theta$, for linearly polarized radiation, as a function $\theta$. Also shown in Fig. 1(d) is a fit to $V_D = A + C \cos^2(\theta - \theta_0)$ that is used to extract $\theta_0$. Fig. 1(e) shows the variation of $\theta_0$ with the frequency, $f$, with the analyzer in place of the specimen. Here, $\theta_0 \leq 10^\circ$ for $34 \leq f \leq 44 \text{GHz}$. This result shows that, without the sample, the polarization at the sample-location follows expectations, within an experimental uncertainty of approximately $10^\circ$.

Figure 2 (a) shows the dark- and photo-excited-diagonal resistance $R_{xx}$ vs. $B$. Here, the photo-excited measurement was carried out with microwave frequency $f = 39 \text{GHz}$ and microwave power $P = 0.32 \text{mW}$, and the MW-antenna parallel to the Hall bar long-axis, i.e., $\theta = 0^\circ$. Fig 2(a) shows once again a well-known negative magnetoresistance to $B = 0.075 \text{Tesla}$ in the high mobility specimen in the dark condition.[8] In Fig. 2(a), the labels $P1$, $V1$, and $P2$, identify the oscillatory extrema that are examined in Fig. 2(b), (c), and (d), respectively. Fig. 2(b) and (d) show that the photo-excited $R_{xx}$ (i.e., “w/ MW”) traces lie above the dark (i.e., “w/o MW”) $R_{xx}$, traces at the resistance maxima for all $\theta$. Further, the photo-excited $R_{xx}$ at $P1$ and $P2$ fits the function
The principal maxima have been labelled $P_1$ and $P_2$, and the minimum is $V_1$. (b), (c), and (d) show the experimental extremal $R_{xx}$ response at $P_1$, $V_1$, and $P_2$, respectively. (b) and (d) show that, at the maxima $P_1$ and $P_2$, $R_{xx}$ under photoexcitation exceeds the dark $R_{xx}$. On the other hand, at $V_1$, the $R_{xx}$ under photoexcitation lies below the dark $R_{xx}$.

$R_{xx}(\theta) = A + C \cos^2(\theta - \theta_0)$, with $\theta_0 = -6.7^0$ and $-1.6^0$, respectively. Fig. 2(c) shows that, at the resistance minimum $V_1$, the w/ MW $R_{xx}$ trace lies below the dark $R_{xx}$ for all $\theta$ as it follows $R_{xx}(\theta) = A - C \cos^2(\theta - \theta_0)$, with $\theta_0 = -8.4^0$. Thus, the greatest radiation-induced $R_{xx}$ oscillatory response occurs here when the antenna is approximately parallel or anti-parallel to the Hall bar long-axis.[21] Here, it is worth noting that the period and the phase of the radiation-induced magnetoresistance oscillations appear not to be influenced by $\theta$, although the amplitude of the oscillatory response is strongly sensitive to it.

Next, we compare experimental results obtained under magnetic field reversal. Thus, Fig. 3(a) shows the $R_{xx}$ vs. $B$ with $f = 40\text{GHz}$ over the $B$-range $-0.25 \leq B \leq 0.25T$. These data are exhibited to compare the relative extremal angular response for positive and negative $B$. As in Fig. 2, extrema of interest have been labelled in Fig. 3(a), here as $P^+1$, $V^+1$ and $P^+2$ for those in the domain $B > 0$, and $P^-1$, $V^-1$ and $P^-2$ for the extrema in the domain $B < 0$. As in Fig. 2, the angular response of the extrema can be fit with $R_{xx}(\theta) = A \pm C \cos^2(\theta - \theta_0)$. However, the fit extracted $\theta_0$ here differ substantially from zero, well beyond experimental uncertainty. Indeed, a close inspection suggests that the $\theta_0$ depends upon the magnetic field $B$ and its orientation $\text{sgn}(B)$. For example, we find that $\theta_0 = 64.4^0$ for $P^-1$ and $\theta_0 = 47^0$ for $P^+1$. Such a large difference in $\theta_0$ due to magnetic field reversal is unexpected. Here, note that since the MW antenna is far from the magnet, and well isolated from the magnetic field, the magnetic field is not expected to influence the polarization of the microwaves at launch. Further, the stainless steel microwave waveguide is not known to (and we have also not seen it) provide a microwave frequency, magnetic field, and magnetic-field-orientation dependent rotation to the microwave polarization. Thus, the $\theta_0$ shift depending on $B$ and $\text{sgn}(B)$ looks to be a sample effect.

Next, the role of the microwave power in the polarization sensitivity is examined in Fig. 4. Fig. 4(a) exhibits, for $f = 37\text{GHz}$, $R_{xx}$ vs. $B$ with $P = 0.32\text{mW}$, along with the dark curve. At the principal maximum $P_1$ and the principal minimum $V_1$, we examine the variation of $R_{xx}$ with $\theta$, for different values of $P$. Fig. 4(b) shows $R_{xx}$ vs. $\theta$ at $P_1$ with $P = 0.32, 1.0$, and $3.16\text{mW}$, and Fig. 4(c) shows the same at $V_1$. Note that $\theta_0 = 37^0$ for $P_1$ here at $f = 37\text{GHz}$, which differs from the $\theta_0 = -6.7^0$ for $V_1$.
for $P_1$ observed at $f = 39\,\text{GHz}$ (see Fig. 2), and $\theta_0 = 47^\circ$ for $P^+1$ at $f = 40\,\text{GHz}$ (see Fig. 3). Yet, Fig. 4(b) shows that the $\theta_0$ does not change with the microwave power $P$. At $P = 0.32\,\text{mW}$ in Fig. 4(c), $R_{xx}$ exhibits simple sinusoidal variation at the $V1$ minimum, as in Fig. 2 and Fig. 3. However, at $P = 3.16\,\text{mW}$, new peaks appear in Fig. 4(c) [but not in Fig. 4(b)], in the vicinity of $\theta = 45^\circ$ and $\theta = 225^\circ$, where none were evident in the $P = 0.32\,\text{mW}$ trace.

The data exhibited above showed that the phase shift, $\theta_0$, can vary with $f$, $B$, and sign of $B$. Next, we report results obtained on either sides of the Hall bar device, and compare $\theta_0$ obtained by measuring the angular dependence of the $R_{xx}$. Note that these measurements were carried out on a Hall bar device oriented perpendicular to the microwave antenna at the outset. Thus, the starting angle for $R_{xx}$ vs. $\theta$ measurements is $-90^\circ$ (see Fig. 5). At the top of Fig. 5, the dark and photoexcited $R_{xx}(B)$ response of the left side of the Hall device, $R^L_{xx}$ [see Fig. 5(a)] and the right side of the Hall bar device, $R^R_{xx}$ [see Fig. 5(b)] are shown at $f = 43\,\text{GHz}$ with $P = 0.5\,\text{mW}$ and $\theta = -90^\circ$. Here, once again, $\theta = -90^\circ$ indicates that the MW-antenna is perpendicular to the long axis of the Hall bar. The $R^L_{xx}$ vs. $\theta$ traces for $f = 43\,\text{GHz}$ and $P = 0.32\,\text{mW}$ at the first ($P_1$) and second ($P_2$) maxima are shown in Fig. 5(c) and 5(g), respectively. Similarly, the $R^R_{xx}$ vs. $\theta$ traces for $f = 43\,\text{GHz}$ and $P = 0.32\,\text{mW}$ at $P_1$ and $P_2$ are shown in Fig. 5(d) and 5(h), respectively. According to Fig. 5(c) and 5(d), $\theta_0$ for $R^L_{xx}$ and $R^R_{xx}$ are $8.9^\circ$ and $1.6^\circ$, respectively, at $P_1$, and they are $-5.5^\circ$ and $-5.3^\circ$, respectively, at $P_2$. Also, the $R_{xx}$ vs. $\theta$ at $V1$ for both sides of the sample [Fig. 5(e) and 5(f)] reveal that $\theta_0 = 1.7^\circ$ for $R^L_{xx}$ and $\theta_0 = -0.5^\circ$ for $R^R_{xx}$. Comparison of the $\theta_0$ values at different extrema on either sides of the Hall bar device indicate that the values are similar for both sides of the device within the experimental uncertainty [see Fig. 1(e)].

**DISCUSSION**

The main features in the exhibited results are therefore: (a) At low $P$, $R_{xx}(\theta) = A \pm C \cos^2(\theta - \theta_0)$ vs. the linear polarization rotation angle, $\theta$, with the ‘+’ and ‘−’ cases describing the oscillatory maxima and minima, respectively, see Fig. 2, 3, and 4. (b) The phase shift in the $R_{xx}(\theta)$ response, i.e., $\theta_0$, varies with $f$, $B$, 

**FIG. 4:** (color online) This figure examines the angular response of $R_{xx}$ at different microwave power levels, $P$. (a) Magnetoresistance oscillations in $R_{xx}$ are exhibited for $f = 37\,\text{GHz}$ with $\theta = 0$ and $P = 0.32\,\text{mW}$, along with the dark $R_{xx}$ curve. (b) shows the $\theta$ dependence of $R_{xx}$ of the principal maximum $P_1$. (c) shows the $\theta$ dependence of $R_{xx}$ of the principal minimum $V1$. In these figures, the w/o MW (w/ MW) traces indicate the sample response in the absence (presence) of microwave photo-excitation. Note that, in (c), additional peaks occur near $\theta = 45^\circ$ and $\theta = 225^\circ$ at $P = 3.16\,\text{mW}$. 

**FIG. 5:** (color online) This figure exhibits the angular dependence of the diagonal resistance on the left and right sides of the Hall bar device, see panel (a) inset. Dark- and photoexcited- $R_{xx}$ are shown for the (a) left side, $R^L_{xx}$, and (b) right side, $R^R_{xx}$, at $f = 43\,\text{GHz}$ with $P = 0.5\,\text{mW}$ and $\theta = -90^\circ$. Panels (c), (e), and (g) show the $\theta$ dependence of the $R^L_{xx}$ for $P = 0.32\,\text{mW}$ at the first maximum ($P_1$), first minimum ($V1$), and second maximum ($P_2$), respectively. Similarly, panels (d), (f), and (h) show the $\theta$ dependence of the $R^R_{xx}$ for $P = 0.32\,\text{mW}$ at $P_1$, $V1$, and $P_2$, respectively. Phase shifts obtained for the two sides of the Hall bar, $R^L_{xx}$ and $R^R_{xx}$, show similar values within the experimental uncertainty at $f = 43\,\text{GHz}$. 

This page contains diagrams and figures illustrating the angular dependence of the diagonal resistance on the Hall bar device. The data exhibit simple sinusoidal variation with angular dependence for different microwave power levels and at specific angles. The figures show the variation of $R_{xx}$ with $\theta$ for both left ($R^L_{xx}$) and right ($R^R_{xx}$) sides of the Hall bar device at 43 GHz with different microwave powers. The phase shift $\theta_0$ is also shown, indicating the relationship between the microwave power and the angular response of the device. The figures highlight the oscillatory maxima and minima due to linear polarization rotation, with $\theta_0$ varying with $f$, $B$, and $P$. The insets in the figures provide additional context and detail for the main results.
and the sign of $B$ (compare Figs. 2, 3 and 4). Yet, $\theta_0$ appears insensitive to the microwave power (see Fig. 4). (c) At higher radiation power, the principal resistance minimum exhibits additional extrema vs. $\theta$ [see Fig. 4(c)]. Point (a) demonstrates a strong sensitivity in the radiation-induced magnetoresistance oscillations to the sense of linear microwave polarization, in qualitative agreement with the radiation driven electron orbit model when $\gamma < \omega = 2\pi f$ [29, 30]. Such sinusoidal variation of the amplitude of the radiation induced magnetoresistance oscillations could also be consistent with the non-parabolicity model (see Fig. 1 of Ref. [25]).

As already mentioned, the displacement model also suggests a linear polarization sensitivity [24]. Consequently, the polarization angle dependence reported here can be considered to be consistent with the displacement model as well. Yet, the experimental feature that the oscillations do not vanish completely at $\theta = 90^\circ$ [see, for example, Fig. 2(b), (c), and (d)] seems not to rule out the existence of a linear-polarization-immune-term in the radiation-induced transport. Points (b) and (c) mentioned above are also interesting. One might also try to understand point (b), for example, in the displacement model. Here, polarization sensitivity [24] is due to the inter-Landau level contribution to the photo-current. In these experiments, the orientation of $E_\omega$ is set by the antenna within the uncertainty indicated in Fig. 1(e). The orientation of $E_{DC}$ is variable and set by the $B$-dependent Hall angle, $\theta_H = \tan^{-1}\langle \sigma_{\parallel 0}/\sigma_{xx} \rangle$, with respect to the Hall bar long-axis. If a particular orientation between $E_\omega$ and $E_{DC}$ is preferred, say, e.g., $E_\omega \perp E_{DC}$ or $E_\omega // E_{DC}$, for realizing large radiation-induced magnetoresistance oscillations, and the Hall angle changes with $B$, then a non-zero $\theta_0$ and a variation in $\theta_0$ with $B$ might be expected. However, the observed variations in $\theta_0$ seem much greater than expectations since $\theta_H \approx 90^\circ$ in this regime. The change in $\theta_0$ upon $B$-reversal is also unexpected, and this feature identifies a possible reason for the asymmetry in the amplitude of $R_{xx}$ under $B$ reversal often observed in such experiments. Consider the typical $R_{xx}$ vs. $B$ measurement sweep, which occurs at a fixed $\theta$. If peak response occurs at different $\theta_0$ for the two field directions, then the oscillatory $R_{xx}$ amplitudes would not be the same for positive and negative $B$. The observed $\theta_0$ variations seem to suggest an effective microwave polarization rotation in the self-response of the photoexcited Hall bar electron device. Since $\theta_0 \approx \pi/4$, see Fig. 3 and 4, $B \approx 0.1T$, and the thickness of the 2DES lies in the range of tens of nanometers, such a scenario would suggest giant effective polarization rotation in this high mobility 2DES.

Finally, we reconcile our observations with other reports on this topic. [14, 15] Ref. [14] reported circular and linear polarization immunity in the radiation-induced magneto-resistance oscillations. Their measurements were carried out on $4 \times 4mm^2$ square shaped specimens, with width-to-length ratio of one. [14] In such a square shaped specimen with point contacts, the current stream lines are expected to point in different directions over the face of the sample. Then, the variable angle between the linear microwave polarization and the local current orientation could possibly serve to produce an effectively polarization averaged measurement, leading to apparent linear polarization immunity. Ref. [15] examined the interference of magnetointersubband oscillations and the microwave radiation-induced magneto-resistance oscillations, and suggested a polarization immunity in the observed interference effect. Since the effect examined by Wiedmann et al. [15] differs substantially from the conventional radiation-induced magnetoresistance oscillations, we subscribe to the opinion that there need not be an obvious contradiction that needs to be addressed here. At the same time, we note that some experimental details, such as sample geometry and the method for changing the polarization, are needed to make a further meaningful comparison. Finally, measurements carried out on L-shaped specimens [9] led to the conclusion that the phase and the period of the microwave-induced magnetoresistance oscillations are independent of the relative orientation of the microwave polarization and the current [9], and this observation is consistent with the initial report [3] and the results reported here.

**CONCLUSION**

In conclusion, experiments identify a strong sinusoidal variation in the diagonal resistance $R_{xx}$ vs. $\theta$, the polarization rotation angle, at the oscillatory extrema of the microwave radiation-induced magnetoresistance oscillations [22, 24, 25, 29, 30]. The results provide new evidence for the linear polarization sensitivity in the amplitude of the radiation-induced magnetoresistance oscillations.

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[1] M. Tinkham, Introduction of Superconductivity, 2nd. ed. (McGraw-Hall, New York, 1990).

[2] R. E. Prange and S. M. Girvin, The Quantum Hall Effect, 2nd. ed. (Springer, New York, 1990).
[3] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayananmurti, W. B. Johnson, and V. Umansky, Nature (London) 420, 646 (2002); Phys. Rev. Lett. 92, 146801 (2004); Phys. Rev. B 69, 193304 (2004); R. G. Mani, V. Narayananmurti, K. von Klitzing, J. H. Smet, W. B. Johnson, and V. Umansky, ibid. 69, 161306 (2004); ibid. 70, 155310 (2004).

[4] M. A. Zudov, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. 90, 046807 (2003).

[5] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayanamurti, and V. Umansky, Bull. Am. Phys. Soc. 46, p. 972 (2001); [http://flux.aps.org/meetings/YR01/MAR01/abs/S7750003.htm].

[6] R. R. Du, M. A. Zudov, C. L. Yang, L. N. Pfeiffer, and K. W. West, Physica E (Amsterdam) 22, 7 (2004).

[7] P. D. Ye, L. W. Engel, D. C. Tsui, J. A. Simmons, J. R. Wendt, G. A. Vawter, and J. L. Reno, Appl. Phys. Lett. 79, 2193 (2001).

[8] R. G. Mani, J. H. Smet, K. von Klitzing, V. Narayananmurti, W. B. Johnson, and V. Umansky, Physica E (Amsterdam) 22, 1 (2004); ibid. 25, 189 (2004); Appl. Phys. Lett. 85, 4962 (2004); Phys. Rev. B 72, 075327 (2005); Appl. Phys. Lett. 91, 132103 (2007); Appl. Phys. Lett. 92, 102107 (2008).

[9] M. Oswald and J. Oswald, Intl. J. Mod. Phys. B 18, 3489 (2004).

[10] A. E. Kovalev, S. A. Zvyagin, C. B. Bowers, J. L. Reno, and J. A. Simmons, Sol. St. Comm. 130, 379 (2004).

[11] S. A. Studenikin, M. Potemski, P. T. Coleridge, A. S. Sachrajda, and Z. R. Wasilewski, Sol. St. Comm. 129, 341 (2004); S. A. Studenikin, A. S. Sachrajda, J. A. Gupta, Z. R. Wasilewski, O. M. Fedorych, M. Byszewski, D. K. Maude, M. Potemski, M. Hilke, K. W. West, and L. N. Pfeiffer, Phys. Rev. B 76, 165321 (2007).

[12] B. Simovic, C. Ellenberger, K. Ensslin, and W. Wegscheider, Phys. Rev. B 71, 233303 (2005).

[13] 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).

[14] S. Wiedmann, G. M. Gusev, O. E. Raichev, T. E. Lamas, A. K. Bakarov, and J. C. Portal, Phys. Rev. B 78, 121301(R) (2008).

[15] R. G. Mani, W. B. Johnson, V. Umansky, V. Narayananmurti, and K. Ploog, Phys. Rev. B 79, 205320 (2009).

[16] O. M. Fedorych, M. Potemski, S. A. Studenikin, J. A. Gupta, Z. R. Wasilewski, and I. A. Dmitriev, Phys. Rev. B 81, 201302(R) (2010).

[17] D. Konstantinov and K. Kono, Phys. Rev. Lett. 103, 266808 (2009); Phys. Rev. Lett. 105, 226801 (2010).

[18] R. G. Mani, C. Gérard, S. Schmutz, W. Wegscheider, and V. Umansky, Phys. Rev. B. 81, 125320 (2010).

[19] A. N. Ramanayaka, R. G. Mani, and W. Wegscheider, Phys. Rev. B 83, 165303 (2011).

[20] R. G. Mani, A. N. Ramanayaka, and W. Wegscheider, Phys. Rev. B 84, 085308 (2011).

[21] A. C. Durst, S. Sachdev, N. Read, and S. M. Girvin, Phys. Rev. Lett. 91, 086803 (2003).

[22] V. Ryzhii and R. Suris, J. Phys.: Cond. Matt. 15, 6855 (2003).

[23] A. A. Koulakov and M. E. Raikh, Phys. Rev. B 68, 115324 (2003).

[24] X. L. Lei and S. Y. Liu, Phys. Rev. Lett. 91, 226805 (2003); X. L. Lei and S. Y. Liu, Phys. Rev. B 72, 075345 (2005).

[25] I. A. Dmytriiev, M. G. Vavilov, I. L. Aleiner, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. B 71, 115316 (2005).

[26] J. Inarrea and G. Platero, Phys. Rev. Lett. 94, 016806 (2005).

[27] J. Inarrea and G. Platero, Phys. Rev. B 76, 073311 (2007).

[28] J. Inarrea and G. Platero, J. Phys. Conf. Ser. 210, 012042 (2010).

[29] A. D. Chepeliantskii, A. S. Pikovsky, and D. L. Shepelyansky, Eur. Phys. J. B 60, 225 (2007); A. D. Chepeliantskii and D. L. Shepelyansky, Phys. Rev. B 80, 241308 (2009).

[30] I. G. Finkler and B. I. Halperin, Phys. Rev. B 79, 085315 (2009).

[31] I. A. Dmytriiev, M. Khodas, A. D. Mirlin, D. G. Polyakov, and M. G. Vavilov, Phys. Rev. B 80, 165327 (2009).

[32] D. Hagenmüller, S. de Librato, and C. Ciuti, Phys. Rev. B 81, 235303 (2010).

[33] S. A. Mikhailov, Phys. Rev. B 83, 155303 (2011); ibid. 71, 035320 (2005).

[34] N. H. Lindner, G. Refael, and V. Galitski, Nat. Phys. 7, 490 (2011).

[35] Z. Gu, H. A. Fertig, D. P. Arovas, and A. Auerbach, Phys. Rev. Lett. 107, 216601 (2011).

[36] C. Nayak, S. H. Simon, A. Stern, M. Freedman, S. Das Sarma, Rev. Mod. Phys. 80, 1083 (2008).

[37] I. Zutic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004).