RAPID COMMUNICATIONS

PHYSICAL REVIEW B **91**, 201301(R) (2015)

Strong transport anisotropy in Ge/SiGe quantum wells in tilted magnetic fields

Q. Shi,[1] M. A. Zudov,[1,*] C. Morrison,[2] and M. Myronov[2]

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

[2]*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*

(Received 27 August 2014; revised manuscript received 18 February 2015; published 8 May 2015)

We report on strong transport anisotropy in a two-dimensional hole gas in a Ge/SiGe quantum well, which emerges only when both perpendicular and in-plane magnetic fields are present. The ratio of resistances, measured along and perpendicular to the in-plane field, can exceed 3×10^4. The anisotropy occurs in a wide range of filling factors where it is determined *primarily* by the tilt angle. The lack of significant anisotropy without an in-plane field, easy tunability, and persistence to higher temperatures and filling factors set this anisotropy apart from nematic phases in GaAs/AlGaAs.

DOI: 10.1103/PhysRevB.91.201301 PACS number(s): 73.63.Hs, 73.40.−c, 73.43.Qt

Strong transport anisotropies were experimentally discovered in a high-mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures subject to strong perpendicular magnetic fields and low temperatures ($T < 0.1$ K) [1,2]. This remarkable phenomenon is marked by the resistivity minima (maxima) in the easy (hard) transport direction near half-integer filling factors, $\nu = 2N + 1 \pm 1/2$ ($2 \leqslant N \leqslant 6$), where N is the Landau level index. The effect has been interpreted in terms of "stripes" [3–5], or a nematic phase [6–8], formed due to an interplay between exchange and direct Coulomb interactions. The origin of the native anisotropy, i.e., how its axes are chosen, is still being debated [9,10].

It is well known that an in-plane magnetic field $B_\parallel$ applied along the easy direction usually switches the anisotropy axes [11–14], aligning the hard axis parallel to $B_\parallel$. Applying $B_\parallel$ along the hard axis could either increase or decrease the anisotropy [11,12,15] and, sometimes, also switch easy and hard axes [11]. In addition, $B_\parallel$ can induce anisotropy in isotropic states, such as fractional quantum Hall (QH) states at $\nu = 5/2, 7/2$ [11,12] and $\nu = 7/3$ [16]. When $B_\parallel$ is applied, these states either become anisotropic compressible states or the anisotropy coexists with the QH effect [16–18]. The effect of $B_\parallel$ can also depend on its orientation with respect to the crystallographic axes, even when the initial state is isotropic [19].

Another class of $B_\parallel$-induced anisotropies appears at *integer* ν, when two Landau levels are brought into coincidence [21–23]. For example, Ref. [21] reported strong anisotropy at $\nu = 4$ of a 2DEG in Si/SiGe in a narrow range of tilt angles, with the hard axis along $B_\parallel$. Similar observations were made in wide GaAs/AlGaAs quantum wells with two occupied subbands [22,23]. However, we are not aware of any reports that $B_\parallel$ can induce significant anisotropy near a half-integer ν in a wide range of $N \geqslant 2$ in originally isotropic 2D systems.

In this Rapid Communication we report on strongly anisotropic transport in a 2D hole gas (2DHG) in a high-mobility Ge/SiGe quantum well [24–27]. While no significant anisotropy is observed in either purely perpendicular or purely parallel B (up to at least $B = 10$ T), tilted B introduces a dramatic anisotropy. Remarkably, the anisotropy emerges almost everywhere, except for QH states, with the hard (easy) axis oriented parallel (perpendicular) to $B_\parallel$, and is largely controlled by a single parameter, the tilt angle θ, up to $N \sim 20$. With $\mathbf{B} = (B_x, 0, B_z)$ and $\theta = \tan^{-1}(B_x/B_z) = 80^\circ$, the resistance ratio R_{xx}/R_{yy} reaches 3×10^4 at $\nu = 9/2$. Although the emergence of anisotropy naturally hints on a stripe phase, our findings differ from observations in GaAs in several important aspects, including the lack of significant anisotropy at $B_\parallel = 0$, easy tunability by θ, and persistence to much higher N and T.

Unless otherwise noted, the presented data were obtained on a $\sim 5 \times 5$ mm square sample fabricated from a fully strained, $\sim$20-nm-wide Ge quantum well grown by reduced pressure chemical vapor deposition on a relaxed $Si_{0.2}Ge_{0.8}$/Ge/Si(001) virtual substrate [24–27]. At $T = 0.3$ K, our 2DHG has a density $p \approx 2.8 \times 10^{11}$ cm^{-2} and mobility $\mu \approx 1.3 \times 10^6$ cm^2/V s. The resistances $R_{xx} \equiv R_{\langle 1\bar{1}0\rangle}$ and $R_{yy} \equiv R_{\langle 110\rangle}$ were measured by a low-frequency lock-in technique.

Before presenting our results, we briefly discuss how our 2DHG in Ge/SiGe compares to 2D systems in GaAs/AlGaAs. First, Ge (GaAs) has a diamond (zinc blende) crystal structure which has (lacks) an inversion center. Second, the perpendicular component of the g factor in Ge is much larger than in GaAs, while its parallel component is zero [28], resulting in a much larger, but $B_\parallel$-independent, Zeeman energy. On the other hand, the band structure in our 2DHG is relatively simple; the light hole band is pushed down by strain and only the heavy hole band, with an effective mass $m^\star \approx 0.09 m_e$ [25,29,30], is populated. In this respect, a 2DHG in Ge/SiGe is more akin to a 2DEG than to a 2DHG in GaAs/AlGaAs.

In Fig. 1 we present R_{xx} and R_{yy} vs B_z at $\theta = 0$ and $T = 0.3$ K. As shown in the inset, quantum oscillations corresponding to even (odd) ν start to develop at $B_z \approx 0.1$ T ($\approx$0.25 T). At higher B_z, both R_{xx} and R_{yy} show QH states at all integer ν, attesting to the excellent quality of our 2DHG [31]. While R_{xx} and R_{yy} differ by about a factor of 3 at $B_z = 0$, no strong anisotropy is observed at $B_z \gtrsim 0.1$ T. However, as we show next, once $B_\parallel$ is introduced, a remarkably strong anisotropy sets in.

In Figs. 2(a) and 2(b) we present R_{xx} and R_{yy}, respectively, versus B_z (bottom) and ν (top), for different θ with $B_\parallel = B_x$. We observe that with increasing θ, R_{xx} (R_{yy}) increases (decreases) almost everywhere except at the QH states. At $\nu = 9/2$ and $\theta = 80^\circ$ the resistance ratio reaches $R_{xx}/R_{yy} \simeq 3 \times 10^4$ ($R_{xx} \approx 2.6$ kΩ, $R_{yy} < 0.1$ Ω). When $B_\parallel = B_y$, the

*Corresponding author: zudov@physics.umn.edu

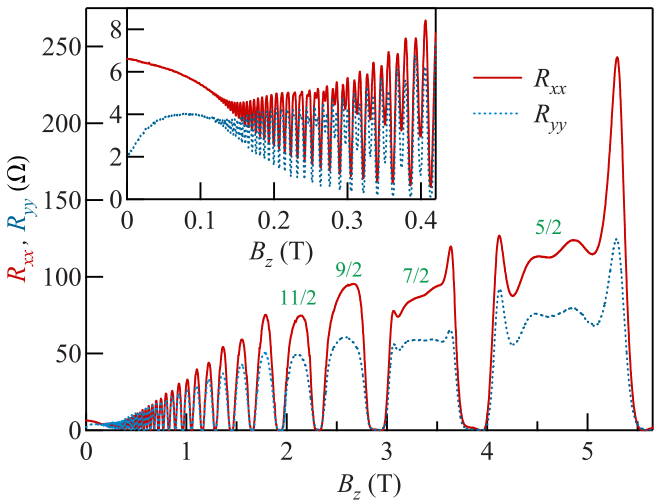

FIG. 1. (Color online) R_{xx} (solid line) and R_{yy} (dotted line) vs B_z at $\theta = 0$ and $T = 0.3$ K.

hard and easy axes switch places, i.e., R_{xx} decreases and R_{yy} increases, showing an almost identical dependence on θ. Since the hard (easy) axis is always parallel (perpendicular) to $B_\parallel$, the sole cause of the observed anisotropy is tilting the sample. The intrinsic zero-field anisotropy, on the other hand, seems to be irrelevant.

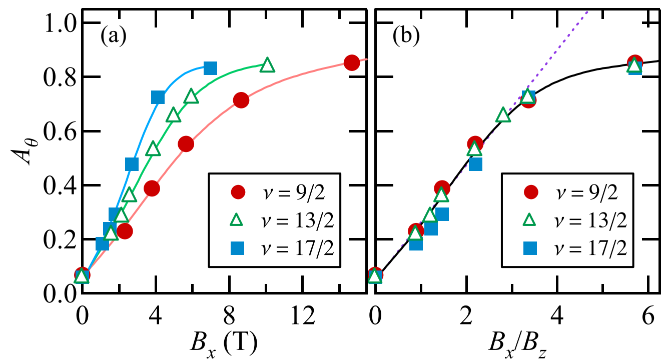

FIG. 3. (Color online) A_θ vs (a) B_x and (b) B_x/B_z at $\nu = 9/2$, 13/2, and 17/2. Solid lines are guides for the eyes. The dotted line is drawn at $A_\theta = 0.05 + 0.21\tan\theta$.

We define the anisotropy as $A_\theta \equiv (\rho_{xx}/\rho_{yy} - 1)/(\rho_{xx}/\rho_{yy} + 1)$, where ρ_{xx}/ρ_{yy} is found using $(\pi\sqrt{\rho_{xx}/\rho_{yy}}/4 - \ln 2)e^{\pi\sqrt{\rho_{xx}/\rho_{yy}}} \approx 4R_{xx}/R_{yy}$ [32]. In Fig. 3(a) we present A_θ vs B_x for $\nu = 9/2$, 13/2, and 17/2. We find that A_θ starts at $A_\theta \approx 0.05$, increases approximately linearly with B_x, and eventually saturates. We observe that at higher ν, smaller B_x is needed to induce the same A_θ. Remarkably, the data at all ν can be well described by a common dependence on $B_x/B_z = \tan\theta$. Indeed, as illustrated

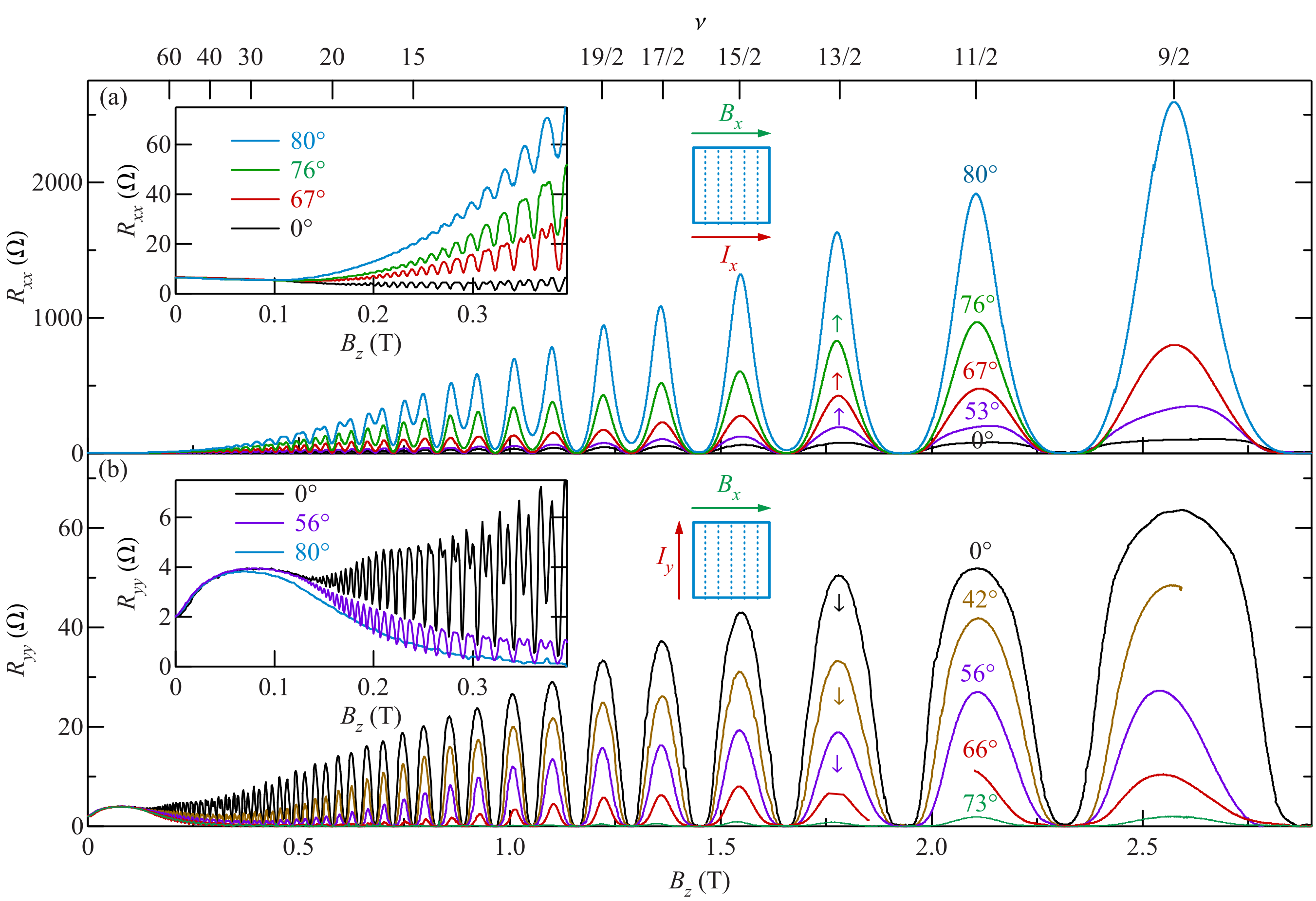

FIG. 2. (Color online) (a) R_{xx} and (b) R_{yy} at different θ vs B_z (bottom) and ν (top) at $T \approx 0.3$ K.

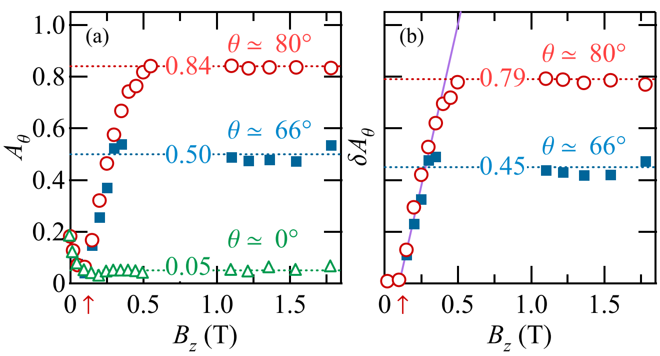

FIG. 4. (Color online) (a) A_θ vs B_z for $\theta \simeq 0°$, 66°, and 88°. (b) δA_θ vs B_z for 66° and 88°. The solid line represents $\delta A_\theta = (B_z - B_0)/B_\star$, where $B_0 = 0.1$ T and $B_\star = 0.4$ T.

in Fig. 3(b), A_θ vs B_x/B_z for all ν fall onto a single curve. Such a dependence is quite remarkable and we are not aware of similar findings in GaAs. The dotted line, drawn at $A_\theta = 0.05 + 0.21 B_x/B_z$, illustrates that A_θ increases roughly linearly until $B_x/B_z \approx 3$.

To see how A_θ evolves with B_z, we construct Fig. 4(a), showing $A_\theta(B_z)$, for $\theta = 80°$, 66°, and 0°. Below 0.1 T, A_θ is independent of θ and decreases with B_z. At higher B_z, A_θ increases and saturates at $\approx 0.84\,(0.50)$ for $\theta = 80°\,(66°)$. In Fig. 4(b) we present $\delta A_\theta = A_\theta - A_{\theta=0°}$, demonstrating that at $B_z \lesssim B_0 = 0.1$ T, $B_\parallel$ does not induce any anisotropy. A roughly linear growth of δA_θ with B_z follows $\delta A_\theta = (B_z - B_0)/B_\star$, where $B_\star = 0.4$ T (cf. the solid line). The data at *both* angles are described well by this dependence until δA_θ saturates at $B_z \approx B_\theta \approx 0.5\,(0.3)$ T at $\theta = 80°\,(66°)$. We thus conclude that at $B_0 < B_z < B_\theta$, A_θ is controlled primarily by B_z. At $B_z > B_\theta$, A_θ is independent of both B_z and B_x for a given θ, which again confirms that A_θ is controlled by θ alone. In contrast, the native anisotropy in GaAs increases with B_z until it vanishes at $N < 2$.

We next demonstrate that the observed anisotropy is remarkably robust against temperature. Figure 5 shows R_{xx} [Fig. 5(a)] and R_{yy} [Fig. 5(b)] measured in a 17 nm-wide

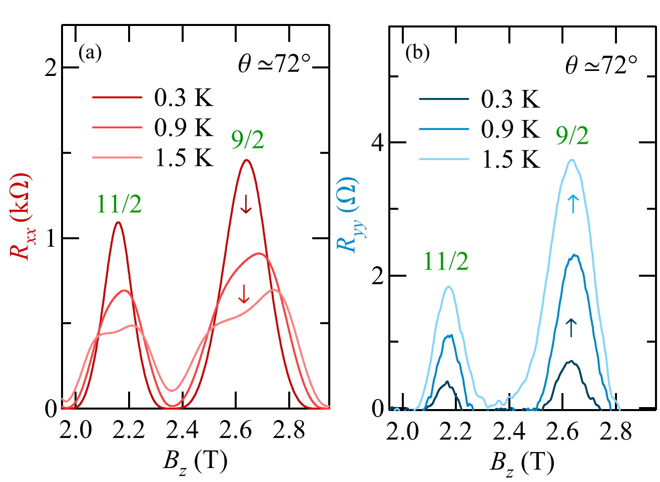

FIG. 5. (Color online) (a) R_{xx} (in kΩ) and (b) R_{yy} (in Ω) at $\theta \approx 72°$ ($B_\parallel = B_x$) and $T = 0.3$, 0.9, and 1.5 K.

$Ge/Si_{0.16}Ge_{0.84}$ quantum well with $p \approx 2.9 \times 10^{11}$ cm^{-2} and $\mu \approx 1.3 \times 10^6$ cm^2/Vs at $\theta \approx 72°$ ($B_x/B_z \approx 3$) and $T = 0.3$, 0.9 and 1.5 K. At filling factor $\nu = 9/2$, the ratio R_{xx}/R_{yy} exceeds 2000 at $T = 0.3$ K and drops by about an order of magnitude as the temperature is raised to $T = 1.5$ K. This drop occurs due to *both* decreasing R_{xx} *and* increasing R_{yy} (which change much more rapidly than in the isotropic state at $\theta = 0$), suggesting that the anisotropy will vanish completely at a few degrees Kelvin. Interestingly, the R_{xx} maxima at half-integer ν evolve into local minima with increasing T.

While we cannot currently explain why the tilted field induces such strong and robust anisotropy in Ge, below we examine several scenarios. The first obvious scenario is the formation of stripes, similar to those found in GaAs. Indeed, as no significant anisotropy shows up in a pure in-plane magnetic field, we conclude that a perpendicular magnetic field is a necessary ingredient, which sets the observed anisotropy in the same context of nematic physics in 2D systems. We recall that the original prediction of the stripe phase [3,4] *did not* specify any preferred direction in the 2D plane, i.e., it predicted randomly oriented stripe domains and no anisotropy on a macroscopic scale. Thus, one possibility is that $B_\parallel$ aligns these preexisting stripe domains, giving rise to macroscopic transport anisotropy. According to Ref. [9], the native anisotropy in GaAs results from a *combination* of Rashba and Dresselhaus spin-orbit interactions. Since Ge lacks the Dresselhaus term, such a symmetry-breaking mechanism does not apply and no native macroscopic anisotropy should be expected. However, introducing an external field, such as $B_\parallel$, could indeed reveal the underlying stripe phase producing observed anisotropy. Furthermore, since $B_\parallel$ is the only symmetry-breaking field in our 2DHG, one can also expect easy tunability and a simple dependence on θ, in contrast to the complex behavior in GaAs caused by the interplay between $B_\parallel$ and other symmetry-breaking fields. We also note that the direction of the anisotropy axes with respect to $B_\parallel$ is consistent with what has been observed in GaAs, especially at initially isotropic filling factors, such as $\nu = 5/2$ and 7/2.

On the other hand, there exist factors which seem to rule out stripes as the origin of anisotropy in our 2DHG, namely, the persistence to much higher N and T compared to that in GaAs. Indeed, at such high temperatures, no strong anisotropy has been observed in GaAs, even under applied $B_\parallel$. Although $B_\parallel$ can change stripe orientation, theory predicts a very small energy difference ($\sim 10^{-2}$ K) between stripes that are parallel and perpendicular to $B_\parallel$ [13,14]. The persistence of anisotropy in Ge up to $T > 1$ K suggests a much larger energy scale. It would be interesting to test the possible existence of anisotropic domains in a purely perpendicular field. For example, nuclear magnetic resonance [33] and pinning mode resonances in the rf conductivity [34] are promising techniques to probe such domains. Other external perturbations, such as direct current, in principle, could also align the domains and lead to macroscopic anisotropy [35].

It is also known that $B_\parallel$ couples the 2D cyclotron motion to the motion in the $\hat{z}$ direction due to finite thickness effects [36]. This coupling results in anisotropy in both the effective mass [37–40] and in the Fermi contour [41,42]. However, for $B_\parallel = B_x$, this mechanism leads to $R_{xx} < R_{yy}$ which is opposite [43] to what we observe in our experiment.

Finally, we mention that surface roughness, in combination with $B_{\parallel}$, was proposed [44] to explain anisotropies near level crossings [21,22]. However, such a scenario is not applicable here since our 2DHG is a single-band system and the vanishing in-plane component of the g factor [28,45] precludes crossings of spin sublevels. Although surface roughness can lead to modest anisotropies at zero field [46] or in pure in-plane magnetic fields [47], it is not clear how it could be linked to the observed anisotropy in the QH regime. Since experiments on Ge quantum wells with much lower mobilities have found no transport anisotropies in tilted B [45], mobility seems to be an important parameter. It is indeed highly desirable to perform measurements on various samples to investigate how the anisotropy depends on mobility, carrier density, strain, symmetry, and width of the quantum well.

In summary, we observed strong anisotropy in the quantum Hall regime of a 2DHG in a Ge/SiGe quantum well. Anisotropy (i) emerges *only* in tilted B and can be easily tuned by θ, (ii) is characterized by R_{xx}/R_{yy} which can be as high as 3×10^4, (iii) persists to high Landau levels, and (iv) requires neither extremely low T nor extremely high mobility. These features set the observed phenomenon apart from the anisotropic phases in GaAs/AlGaAs and, as such, point towards a different mechanism of transport anisotropy, which, for some reason, is suppressed in GaAs. As a result, observation of a distinct type of strongly anisotropic transport in a system other than GaAs represents an important step towards an overall understanding of electronic anisotropies.

We thank G. Jones, S. Hannas, T. Murphy, J. Park, A. Suslov, and D. Smirnov for technical assistance with experiments, and P. Baity for assistance with wire bonding. We thank S. Das Sarma, L. Engel, Z. Jiang, S. Kivelson, K. von Klitzing, A. MacDonald, R. Nicholas, W. Pan, D. Polyakov, M. Shayegan, B. Shklovskii, R. Winkler, and K. Yang for discussions. The work at Minnesota was funded by the U.S. Department of Energy, Office of Basic Energy Sciences, under Grant No. ER 46640-SC0002567. Q.S. acknowledges support from the Allen M. Goldman fellowship. The work at Warwick was supported by a EPSRC funded "Spintronic device physics in Si/Ge Heterostructures" EP/J003263/1 and "Platform Grant" EP/J001074/1 projects. Experiments were performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0654118, by the State of Florida, and by the DOE.

[1] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 394 (1999).
[2] R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Solid State Commun. **109**, 389 (1999).
[3] A. A. Koulakov, M. M. Fogler, and B. I. Shklovskii, Phys. Rev. Lett. **76**, 499 (1996).
[4] M. M. Fogler, A. A. Koulakov, and B. I. Shklovskii, Phys. Rev. B **54**, 1853 (1996).
[5] E. H. Rezayi, F. D. M. Haldane, and K. Yang, Phys. Rev. Lett. **83**, 1219 (1999).
[6] E. Fradkin and S. A. Kivelson, Phys. Rev. B **59**, 8065 (1999).
[7] E. Fradkin, S. A. Kivelson, E. Manousakis, and K. Nho, Phys. Rev. Lett. **84**, 1982 (2000).
[8] E. Fradkin, S. A. Kivelson, M. J. Lawler, J. P. Eisenstein, and A. P. Mackenzie, Annu. Rev. Condens. Matter Phys. **1**, 153 (2010).
[9] I. Sodemann and A. H. MacDonald, arXiv:1307.5489.
[10] S. P. Koduvayur, Y. Lyanda-Geller, S. Khlebnikov, G. Csathy, M. J. Manfra, L. N. Pfeiffer, K. W. West, and L. P. Rokhinson, Phys. Rev. Lett. **106**, 016804 (2011).
[11] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **83**, 824 (1999).
[12] W. Pan, R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **83**, 820 (1999).
[13] T. Jungwirth, A. H. MacDonald, L. Smrčka, and S. M. Girvin, Phys. Rev. B **60**, 15574 (1999).
[14] T. D. Stanescu, I. Martin, and P. Phillips, Phys. Rev. Lett. **84**, 1288 (2000).
[15] K. B. Cooper, M. P. Lilly, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **65**, 241313 (2002).
[16] J. Xia, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Nat. Phys. **7**, 845 (2011).
[17] M. Mulligan, C. Nayak, and S. Kachru, Phys. Rev. B **84**, 195124 (2011).
[18] Y. Liu, S. Hasdemir, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **88**, 035307 (2013).
[19] C. Zhang, T. Knuuttila, Y. Dai, R. R. Du, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **104**, 166801 (2010).
[20] C. Zhang, C. Huan, J. S. Xia, N. S. Sullivan, W. Pan, K. W. Baldwin, K. W. West, L. N. Pfeiffer, and D. C. Tsui, Phys. Rev. B **85**, 241302 (2012).
[21] U. Zeitler, H. W. Schumacher, A. G. M. Jansen, and R. J. Haug, Phys. Rev. Lett. **86**, 866 (2001).
[22] W. Pan, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. B **64**, 121305 (2001).
[23] D. R. Luhman, W. Pan, T. M. Lu, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, J. Phys.: Conf. Ser. **334**, 012006 (2011).
[24] A. Dobbie, M. Myronov, R. J. H. Morris, A. H. A. Hassan, M. J. Prest, V. A. Shah, E. H. C. Parker, T. E. Whall, and D. R. Leadley, Appl. Phys. Lett. **101**, 172108 (2012).
[25] C. Morrison, P. Wisniewski, S. D. Rhead, J. Foronda, D. R. Leadley, and M. Myronov, Appl. Phys. Lett. **105**, 182401 (2014).
[26] M. Myronov, C. Morrison, J. Halpin, S. Rhead, C. Casteleiro, J. Foronda, V. A. Shah, and D. Leadley, Jpn. J. Appl. Phys. **53**, 04EH02 (2014).
[27] M. Myronov, C. Morrison, J. Halpin, S. Rhead, J. Foronda, and D. Leadley, Solid State Electron. (2015), DOI: 10.1016/j.sse.2015.01.012.
[28] R. Winkler, *Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems* (Springer, New York, 2003).

[29] M. A. Zudov, O. A. Mironov, Q. A. Ebner, P. D. Martin, Q. Shi, and D. R. Leadley, Phys. Rev. B **89**, 125401 (2014).

[30] Q. Shi, Q. A. Ebner, and M. A. Zudov, Phys. Rev. B **90**, 161301(R) (2014).

[31] Our 2DHG also reveals fully developed QH states at $\nu = 5/3$, $4/3$, and $2/3$. However, observation of the fractional QH effect in Ge falls outside the scope of the present work and is left for future publication.

[32] S. H. Simon, Phys. Rev. Lett. **83**, 4223 (1999).

[33] B. Friess, V. Umansky, L. Tiemann, K. von Klitzing, and J. H. Smet, Phys. Rev. Lett. **113**, 076803 (2014).

[34] H. Zhu, G. Sambandamurthy, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **102**, 136804 (2009).

[35] J. Gores, G. Gamez, J. H. Smet, L. Pfeiffer, K. West, A. Yacoby, V. Umansky, and K. von Klitzing, Phys. Rev. Lett. **99**, 246402 (2007).

[36] $B_{\parallel}$ is also known to introduce additional Landau level broadening [48, 49].

[37] A. V. Khaetskii and B. I. Shklovskii, Zh. Eksp. Teor. Fiz. **85**, 721 (1983) [Sov. Phys. JETP **58**, 421 (1983)].

[38] L. Smrcka, J. Phys.: Condens. Matter **2**, 8337 (1990).

[39] L. Smrcka and T. Jungwirth, J. Phys.: Condens. Matter **6**, 55 (1994).

[40] A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **85**, 241305(R) (2012).

[41] D. Kamburov, M. Shayegan, R. Winkler, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **86**, 241302 (2012).

[42] D. Kamburov, M. A. Mueed, M. Shayegan, L. N. Pfeiffer, K. W. West, K. W. Baldwin, J. J. D. Lee, and R. Winkler, Phys. Rev. B **88**, 125435 (2013).

[43] S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **84**, 5596 (2000).

[44] J. T. Chalker, D. G. Polyakov, F. Evers, A. D. Mirlin, and P. Wölfle, Phys. Rev. B **66**, 161317 (2002).

[45] I. L. Drichko, V. A. Malysh, I. Y. Smirnov, L. E. Golub, S. A. Tarasenko, A. V. Suslov, O. A. Mironov, M. Kummer, and H. von Känel, Phys. Rev. B **90**, 125436 (2014).

[46] A. H. A. Hassan, R. J. H. Morris, O. A. Mironov, R. Beanland, D. Walker, S. Huband, A. Dobbie, M. Myronov, and D. R. Leadley, Appl. Phys. Lett. **104**, 132108 (2014).

[47] A. V. Goran, A. A. Bykov, and A. I. Toropov, Semicond. Sci. Technol. **23**, 105017 (2008).

[48] A. T. Hatke, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **83**, 081301(R) (2011).

[49] A. Bogan, A. T. Hatke, S. A. Studenikin, A. Sachrajda, M. A. Zudov, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **86**, 235305 (2012).