Interaction between Surface Acoustic Wave and Quantum Hall Effects

Xiao Liu(刘萧)[1], Mengmeng Wu(吴蒙蒙)[1], Renfei Wang(王任飞)[1], Xinghao Wang(王兴豪)[1], Wenfeng Zhang(张文锋)[1], Yujiang Dong(董昱江)[1], Rui-Rui Du(杜瑞瑞)[1,2], Yang Liu(刘阳)[1,3*], and Xi Lin(林熙)[1,3,4*]

[1]*International Center for Quantum Materials, Peking University, Beijing 100871, China*
[2]*Center for Excellence, University of Chinese Academy of Sciences, Beijing 100190, China*
[3]*Hefei National Laboratory, Hefei 230088, China*
[4]*Interdisciplinary Institute of Light-Element Quantum Materials and Research Center for Light-Element Advanced Materials, Peking University, Beijing 100871, China*

(Received 7 February 2024; accepted manuscript online 21 March 2024)

Surface acoustic wave (SAW) is a powerful technique for investigating quantum phases appearing in two-dimensional electron systems. The electrons respond to the piezoelectric field of SAW through screening, attenuating its amplitude, and shifting its velocity, which is described by the relaxation model. In this work, we systematically study this interaction using orders of magnitude lower SAW amplitude than those in previous studies. At high magnetic fields, when electrons form highly correlated states such as the quantum Hall effect, we observe an anomalously large attenuation of SAW, while the acoustic speed remains considerably high, inconsistent with the conventional relaxation model. This anomaly exists only when the SAW power is sufficiently low.

DOI: 10.1088/0256-307X/41/4/047301

Research on charge carrier transport in two-dimensional electron systems (2DES) has unveiled various intriguing quantum phenomena.[1–3] The quantum Hall effect (QHE) is of interest due to its distinctive experimental phenomena: the vanishing of longitudinal resistivity and the precise quantization of Hall resistivity into discrete integers[1] and fractions.[2] Theoretical explanations for the QHE include the formation of an incompressible quantum liquid that carries superflow current, and disorder-induced localization of sparse quasiparticles.[4] At sufficiently large perpendicular magnetic fields, when only several Landau levels are occupied, and in samples with sufficiently high mobility, the Coulomb interaction arranges the sparse quasiparticles into an ordered array named the Wigner crystal.[5–10] Additionally, the stripe and bubble phases represent two other types of electron solids, emerging as collective charge density waves in the $N \geq 1$ spin-resolved Landau levels.[11–13] The interaction between these states and external perturbations, such as microwaves,[14–19] acoustic waves,[20–32] light,[33] in-plane magnetic fields,[34–38] bias voltage,[39] noise,[40] and hydrostatic pressure,[41–43] presents avenues for exploring exotic physics and gaining profound insights into state evolution.

Surface acoustic wave (SAW) provides a contactless approach for investigating the transport properties of 2DES. As SAW propagates on the surface of GaAs/AlGaAs samples, which are piezoelectric, its co-propagating piezoelectric field interacts with the adjacent 2DES through a relaxation process.[44,45] This piezoelectric field will be fully screened when the electronic relaxation time (i.e., the transport lifetime $\tau_{\rm tr}$) is shorter than the acoustic wave period. In the weak-coupling limit, the relaxation model predicts that the SAW attenuation coefficient Γ and its normalized velocity shift $\eta = \Delta v/v_0$ are related with the 2DES conductivity σ_{xx} as follows:

$$\Gamma = k\frac{K^2_{\rm eff}}{2}\frac{\sigma_{xx}/\sigma_{\rm M}}{1+(\sigma_{xx}/\sigma_{\rm M})^2}, \tag{1}$$

$$\eta = \Delta v/v_0 = \frac{K^2_{\rm eff}}{2}\frac{1}{1+(\sigma_{xx}/\sigma_{\rm M})^2}, \tag{2}$$

where $v_0 = v(\sigma_{xx} \to \infty)$ and $K^2_{\rm eff}$ is the effective piezoelectric coupling constant. The characteristic conductivity $\sigma_{\rm M} = v_0(\epsilon) \approx 4\text{–}7\times10^{-7}\,\Omega^{-1}$, with ϵ being the effective dielectric constant.

This relaxation model has been widely used to interpret experimental observations in many previous studies, where the SAW amplitude is large (namely many electrons are confined by the piezo-potential).[20–25,29–31] However, recent experimental observations suggest some insufficiencies when strongly correlated electron solid phases are present.[26–28,32] In this work, we study 2DES using SAW amplitude that is orders of magnitude smaller than previous studies. Our data demonstrate the inadequacy of the relaxation model at low filling factors. We find that the interaction between 2DES and SAW is influenced by the presence of current and changing acoustic power, which are also missed in the relaxation model.

Sample and Methods. Our sample is fabricated from

*Corresponding authors. Email: liuyang02@pku.edu.cn; xilin@pku.edu.cn
© 2024 Chinese Physical Society and IOP Publishing Ltd

a GaAs/AlGaAs single-interface heterostructure grown by molecular-beam epitaxy whose 2DES layer is located approximately 120 nm below the surface. The electron density is $1.12 \times 10^{11}\,\mathrm{cm}^{-2}$ and the low temperature mobility is $\mu \sim 1 \times 10^{6}\,\mathrm{cm}^2\cdot\mathrm{V}^{-1}\cdot\mathrm{s}^{-1}$. The 2DES mesa is a $1.2 \times 1.2\,\mathrm{mm}^2$ square at the center, with four annealed Ge/Au/Ni/Au Ohmic contacts at the corners of the sample. Four interdigital transducers (IDTs), fabricated using maskless laser lithography, are symmetrically arranged around the square mesa. Each IDT consists of 170 pairs of 1 µm wide Al finger electrodes, separated by an interdigitated gap of 1.5 µm. Such an IDT configuration generates SAW with a wavelength of $\lambda = 5\,\mu\mathrm{m}$ if excited at its resonance frequency $f_c = 580.5\,\mathrm{MHz}$; see Fig. 1(b). The aperture of the IDT spans 1220 µm, slightly wider than the mesa. We removed 200-nm-thick AlGaAs below the IDT, including all doping layers, to ensure optimal performance. All the measurements are conducted in a dilution refrigerator whose base temperature is approximately 10 mK.

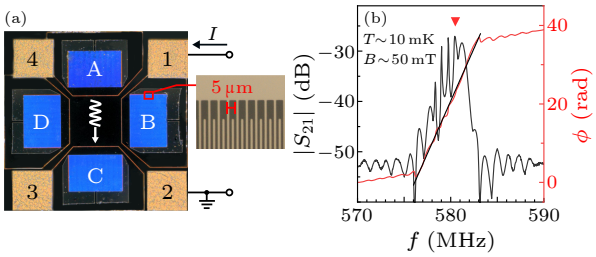

Fig. 1. (a) The image of our sample. The $d_m = 1.2\,\mathrm{mm}$ square van der Pauw mesa with four contacts is defined by wet etching. (b) The frequency spectrum measured by IDT pair A & C. The red triangle marks the resonance frequency $f_c \approx 580.5\,\mathrm{MHz}$, at which all the rest measurements are performed.

The frequency dependence of the amplitude and phase of the transmission coefficient, $|\boldsymbol{S}_{21}|$ and ϕ, is illustrated in Fig. 1(b). The data is measured at 50 mT and fridge base temperature. The low-field SAW velocity can be estimated from the resonance frequency through $v_0 = f_c \cdot \lambda \simeq 2900\,\mathrm{m/s}$, and its total traveling time can be deduced from the phase–frequency relation within the resonance peak $\tau_0 = \partial\phi/\partial(2\pi f) = 0.85\,\mu\mathrm{s}$. This estimated SAW travel distance $d = v_0\tau_0 \simeq 2.5\,\mathrm{mm}$ is consistent with the 2450 µm center-to-center distance between opposite IDTs. A homemade RF lock-in amplifier with high sensitivity and low noise was utilized to monitor the amplitude and phase shift.[46] The SAW velocity shift is calculated as $\eta = \phi/2\pi f_c\tau$, with $\tau \simeq 0.4\,\mu\mathrm{s}$, the SAW traveling time through the 1.2 mm square 2DES mesa.[32] Unless otherwise specified, the input excitation power applied to the IDT is 1 nW.

Results and Discussion. Figures 2(a)–2(c) show the longitudinal magneto-resistance R_{xx} measured using conventional lock-in techniques at 7.3 Hz, the SAW attenuation Γ and velocity shift η in reference with their zero magnetic field values. By comparing Figs. 2(a) and 2(c) data, the SAW results are more reliable and sensitive than the conventional transport measurement. For example, features corresponding to the $\nu = 4/3$ fractional quantum Hall effect are clearly seen in Fig. 2(c) while they are invisible in Fig. 2(a). Although the response of other phases such as CDW in SAW measurement is not well understood, the observed $\nu = 4/3$ feature is more likely a signature of quantum Hall liquid. This is because the formation of CDW phases can cause either anisotropic η or a negative η,[26] which is not the case here. SAW measurement exhibits features even if droplets of quantum Hall liquid appear, while showing transport features requires the quantum Hall region to be sufficiently large so as to conduct the dissipation-less current. The better performance of SAW measurement can also be seen at low magnetic fields, as illustrated in Fig. 3(a). The conductivity of 2DES exhibits Shubnikov–de Haas oscillations, and the oscillation in η starts at a similar field as the best R_{xx}. Enhanced η, seen as maximum in Fig. 2(c), appears at even integer filling factors when the magnetic field exceeds about 0.1 T. Above 0.38 T, maximum develops at odd integer fillings, corresponding to the breaking of spin degeneracy. This is also similar to the R_{xx} data. The fact that acoustic speed increases at integer fillings is consistent with the relaxation model, where the 2DES's screening capability against piezoelectric fields vanishes when it forms an incompressible quantum Hall liquid. The electrons become mobile when the 2DES is compressible at half-integer fillings. They screen the SAW's piezoelectric fields and slow down the sound velocity. It is quite surprising that η almost always equals its zero-field value, despite the fact that the conductivity of 2DES in these high mobility samples vanishes as B^{-2}.[47]

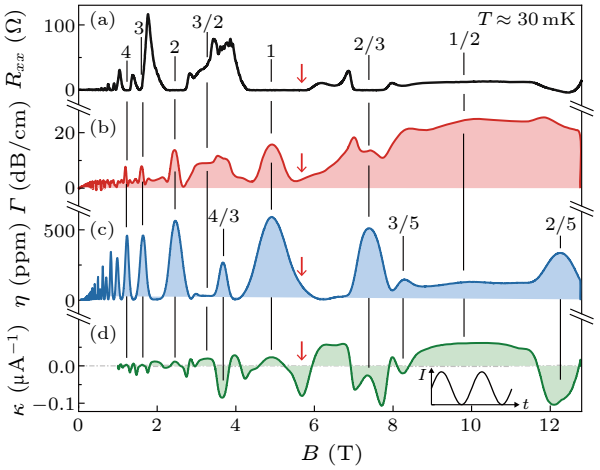

Fig. 2. (a)–(c) The longitudinal resistance R_{xx} measured using conventional 4-point transport measurement, the SAW attenuation coefficient Γ and velocity shift η measured when all contacts are grounded. (d) The current induced SAW velocity shift measured when an oscillating positive current (see the inset) flows between contacts 1 and 2.

We now summarize the η and Γ at integer fillings as a function of their corresponding magnetic fields in Figs. 3(b) and 3(c). We find that η has a clear expo-

nential dependence on $1/B$ over nearly 3 orders of magnitude. Note that the relaxation model is not suitable to describe the interaction between the SAW and the incompressible QHE when the screening is likely caused by creating quasiparticles/quasiholes. One would not be surprised to see the exponential relation $\eta \propto \exp(-\Delta_e/\hbar\omega_c)$ and $\eta \propto \exp(-\Delta_o/E_Z)$ at odd and even filling factors, respectively. By fitting the data in Fig. 3(b), we can deduce the energy that describes this SAW-2DES interaction, $\Delta_e \simeq 14\,\mathrm{K}$ and $\Delta_o \simeq 0.9\,\mathrm{K}$. Here, $\hbar\omega_c$ is the cyclotron energy and E_Z is the Zeeman energy.

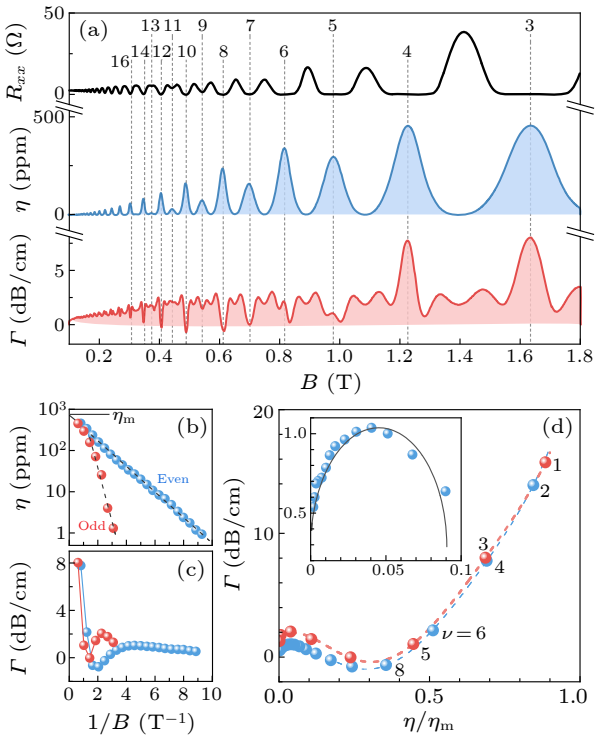

Fig. 3. (a) Expanded plots of η and Γ at low magnetic field. (b) η vs. $1/B$, exhibiting an exponential relation for both even and odd integer filling factors. The red/blue dots are the experimental data at odd/even fillings. The black dashed lines are the fitting curves, see text. (c) Γ vs. $1/B$. (d) The relation between Γ and the normalized velocity shift η/η_m. The inset displays the high filling factors data points and the black line is the best fitting with Eqs. (1) and (2) using $K_{eff}^2 = 1.2 \times 10^{-4}$.

The deviation of our experimental results from the relaxation model is more pronounced in the evolution of the SAW attenuation Γ. When we increase the magnetic field, Γ at integer fillings first increases and reaches its maximum at about 0.2 T before decreasing. This is expected by the relaxation model and the Γ maximum signals that $\sigma_{xx} = \sigma_M$. When we further increase the magnetic fields to above 0.8 T, a peak in Γ appears at integer fillings in contrast to the Γ minimum seen at low fields. This peak becomes dominant at the filling factor $\nu = 4$ and continuously grows larger as we decrease the filling factor.

The anomalously increasing Γ after the low-field peak, seen when $\sigma_{xx} = \sigma_M$, while η monotonically increases, is counterintuitive. The 2DES becomes more incompressible and the SAW-2DES interaction should be even weaker for the QHE at lower fillings. Furthermore, Γ seen at low fillings is much larger than its low field values in all conditions [below 3 dB/cm in Fig. 3(a)]. We also note that at $\nu = 1/2$, $3/2$, where the 2DES is compressible and η equals its zero field value, Γ becomes an order of magnitude larger than its low field values; note that the unit of Γ is logarithmic in Fig. 3. A possible reason could be attributed to the emergence of correlated states stabilized by the strong electron-electron interactions at low filling factors, such as quantum Hall effects, composite fermion Fermi sea, and Wigner crystals. These states may be effective in damping the SAW's piezoelectric fields through mechanisms such as electron-electron scattering, while their long range correlation prevents reducing the acoustic velocity.

We summarize the η and Γ values for even and odd integer filling factors, as depicted in Fig. 3(d). The Γ vs. the normalized velocity shift η/η_m relation is almost the same for the odd and even filling factors. Here, $\eta_m \simeq 663\,\mathrm{ppm}$ is the maximum SAW velocity shift at $1/B = 0\,\mathrm{T}^{-1}$, obtained from fitting the data shown in Fig. 3(b). The relaxation model is only applicable to high filling factor states, see the inset in Fig. 3(d). At low filling factors, Γ increases nearly linearly with η, and we do not observe any sign of saturation in Γ up to $\nu = 1$. As far as we know, a suitable theoretical modeling of the SAW-2DES interaction is missing. We hope that our clear experimental observations can help to stimulate future investigations.

We would like to emphasize that the above observations can only be seen when using extremely low SAW powers, and the presence of a conducting current can also vary the observed Γ and η.[48] In Figs. 4(c) and 4(d), we measured the variations in attenuation coefficient $[\delta\Gamma = \Gamma(I) - \Gamma(0)]$ and velocity shift $[\delta\eta = \eta(I) - \eta(0)]$ as a function of DC current I_{DC} at $\nu = 1$ with various input SAW powers. The variations of Γ and η with SAW power when $I_{DC} = 0$ are depicted in Figs. 4(a) and 4(b).

At $\nu = 1$, Γ decreases by about 15 dB/cm when increasing the SAW power from 1 nW to about 80 nW. That is to say, the anomalous Γ peak seen in Fig. 2(b) can only be seen at sufficiently low SAW amplitude. On the other hand, Γ slightly increases by about 2 dB/cm when we increase the current to almost 1 μA. Meanwhile, increasing SAW amplitude reduces η, while DC current leads to an increasing η. This is rather interesting as the data suggest that SAW and current have opposite effects on the 2DES. Another noteworthy feature in Figs. 4(c) and 4(d) is the fact that the current effect has a clear threshold of about 300 nA in the 1 nW SAW power trace, which disappears at high SAW power.

In order to compare the DC current effect for different phases, we applied a 0.25 Hz, 400 nA peak-to-peak AC current with a 200 nA DC offset between contacts 1 and 2 of the sample. The resulting change in SAW velocity is represented by a normalization parameter $\kappa = \eta_m^{-1} \cdot (\partial\eta/\partial|I|)$. Here κ approaches zero when the QHE is strong, e.g., at

integer $\nu = 1$, 2, 3, etc. or fractional $\nu = 2/3$. This is expected from the threshold feature seen in Fig. 4(b). On the other hand, when the QHE is fragile at $\nu = 4/3$, 2/5, a substantial negative κ is observed, suggesting that the applied current makes the 2DES more efficient in slowing down the acoustic wave.

In Fig. 2(d), κ has a large negative value on the edge of the R_{xx} plateaus. In Figs. 4(a) and 4(b) and Figs. 4(e)–4(f), we focus on one of these negative κ peaks at 5.7 T (marked by arrows in Fig. 2). As we have discussed earlier, increasing SAW power and sending current have opposite effects on η and Γ at $\nu = 1$, but they lead to qualitatively the same outcome at 5.7 T. In both cases, η decreases and Γ increases. We note that the Λ-shape maximum of the η vs. $I_{\rm DC}$ relation at low SAW power becomes flat at high SAW power, opposite to the observed trend at $\nu = 1$. We also would like to point out that the changes in η and Γ tend to saturate at $I_{\rm DC} \gtrsim 700$ nA, while no sign of saturation is seen at $\nu = 1$ until 2 μA, which is still far less than the breakdown current of the $\nu = 1$ QHE.

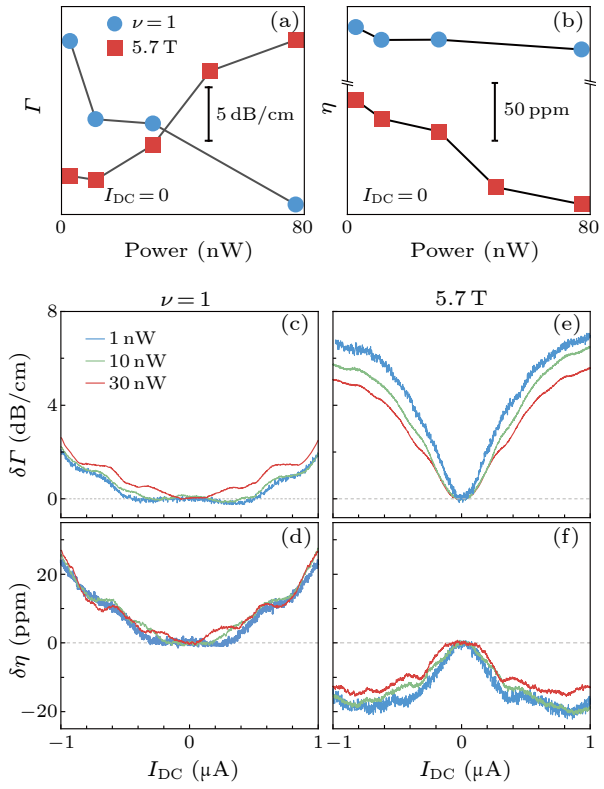

Fig. 4. [(a), (b)] Γ and η with SAW power at zero $I_{\rm DC}$. (c)–(f) The current-induced SAW attenuation variation $\delta\Gamma$ and velocity shift $\delta\eta$ at $\nu = 1$ (left column) and $B = 5.7$ T (right column), using different probing SAW powers.

In conclusion, our systematic study shows that the conventional relaxation model is insufficient in describing the SAW-2DES interaction at very low SAW power and when 2DES forms strongly correlated states. We present as much experimental evidence as possible, and hope that a comprehensive theoretical model can be proposed in the future.

Acknowledgments. This work was supported by the National Key Research and Development Program of China (Grant Nos. 2021YFA1401900 and 2019YFA0308403), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDB33030000), the National Natural Science Foundation of China (Grant Nos. 92065104, 12074010, and 12141001), and the Innovation Program for Quantum Science and Technology (Grant No. 2021ZD0302602) for sample fabrication and measurement.

References

[1] Klitzing K v, Dorda G, and Pepper M 1980 *Phys. Rev. Lett.* **45** 494
[2] Tsui D C, Stormer H L, and Gossard A C 1982 *Phys. Rev. Lett.* **48** 1559
[3] Jain J K 2007 *CompositeFermion (Cambridge: Cambridge University Press)*
[4] Prange R E and Girvin S M 1990 *The Quantum Hall Effect* (New York: Springer)
[5] Wigner E 1934 *Phys. Rev.* **46** 1002
[6] Lozovik Y E and Yudson V 1975 *ZhETF Pisma Redaktsiiu* **22** 26
[7] Lam P K and Girvin S M 1984 *Phys. Rev. B* **30** 473
[8] Levesque D, Weis J J, and MacDonald A H 1984 *Phys. Rev. B* **30** 1056
[9] Willett R L, Stormer H L, Tsui D C, Pfeiffer L N, West K W, and Baldwin K W 1988 *Phys. Rev. B* **38** 7881
[10] Zhu X J and Louie S G 1995 *Phys. Rev. B* **52** 5863
[11] Koulakov A A, Fogler M M, and Shklovskii B I 1996 *Phys. Rev. Lett.* **76** 499
[12] Du R R, Tsui D C, Stormer H L, Pfeiffer L N, Baldwin K W, and West K W 1999 *Solid State Commun.* **109** 389
[13] Lilly M P, Cooper K B, Eisenstein J P, Pfeiffer L N, and West K W 1999 *Phys. Rev. Lett.* **82** 394
[14] Engel L W, Shahar D, Kurdak Ç, and Tsui D C 1993 *Phys. Rev. Lett.* **71** 2638
[15] Chen Y, Lewis R M, Engel L W, Tsui D C, Ye P D, Pfeiffer L N, and West K W 2003 *Phys. Rev. Lett.* **91** 016801
[16] Lewis R M, Chen Y P, Engel L W, Tsui D C, Pfeiffer L N, and West K W 2005 *Phys. Rev. B* **71** 081301
[17] Zhu H, Sambandamurthy G, Chen Y P, Jiang P, Engel L W, Tsui D C, Pfeiffer L N, and West K W 2010 *Phys. Rev. Lett.* **104** 226801
[18] Hatke A, Liu Y, Engel L, Shayegan M, Pfeiffer L, West K, and Baldwin K 2015 *Nat. Commun.* **6** 7071
[19] Hatke A T, Liu Y, Engel L W, Pfeiffer L N, West K W, Baldwin K W, and Shayegan M 2017 *Phys. Rev. B* **95** 045417
[20] Wixforth A, Kotthaus J P, and Weimann G 1986 *Phys. Rev. Lett.* **56** 2104
[21] Wixforth A, Scriba J, Wassermeier M, Kotthaus J P, Weimann G, and Schlapp W 1989 *Phys. Rev. B* **40** 7874
[22] Willett R L, Paalanen M A, Ruel R R, West K W, Pfeiffer L N, and Bishop D J 1990 *Phys. Rev. Lett.* **65** 112
[23] Paalanen M A, Willett R L, Littlewood P B, Ruel R R, West K W, Pfeiffer L N, and Bishop D J 1992 *Phys. Rev. B* **45** 11342
[24] Willett R L, Ruel R R, West K W, and Pfeiffer L N 1993 *Phys. Rev. Lett.* **71** 3846
[25] Willett R L, West K W, and Pfeiffer L N 2002 *Phys. Rev. Lett.* **88** 066801
[26] Friess B, Peng Y, Rosenow B, von Oppen F, Umansky V, von Klitzing K, and Smet J H 2017 *Nat. Phys.* **13** 1124
[27] Friess B, Umansky V, von Klitzing K, and Smet J H 2018 *Phys. Rev. Lett.* **120** 137603

[28] Friess B, Dmitriev I A, Umansky V, Pfeiffer L, West K, von Klitzing K, and Smet J H 2020 *Phys. Rev. Lett.* **124** 117601
[29] Drichko I L, Smirnov I Y, Suslov A V, and Leadley D R 2011 *Phys. Rev. B* **83** 235318
[30] Drichko I L, Smirnov I Y, Suslov A V, Pfeiffer L N, West K W, and Galperin Y M 2015 *Phys. Rev. B* **92** 205313
[31] Drichko I, Smirnov I Y, Suslov A, Galperin Y, Pfeiffer L, and West K 2017 *Low Temp. Phys.* **43** 86
[32] Wu M M, Liu X, Wang R F, Chung Y J, Gupta A, Baldwin K W, Pfeiffer L, Lin X, and Liu Y 2024 *Phys. Rev. Lett.* **132** 076501
[33] Arikawa T, Hyodo K, Kadoya Y, and Tanaka K 2017 *Nat. Phys.* **13** 688
[34] Haug R J, Klitzing K v, Nicholas R J, Maan J C, and Weimann G 1987 *Phys. Rev. B* **36** 4528
[35] Clark R G, Haynes S R, Suckling A M, Mallett J R, Wright P A, Harris J J, and Foxon C T 1989 *Phys. Rev. Lett.* **62** 1536
[36] Engel L W, Hwang S W, Sajoto T, Tsui D C, and Shayegan M 1992 *Phys. Rev. B* **45** 3418
[37] Du R R, Yeh A S, Stormer H L, Tsui D C, Pfeiffer L N, and West K W 1995 *Phys. Rev. Lett.* **75** 3926
[38] Wang P J, Sun J, Fu H L, Wu Y J, Chen H, Pfeiffer L N, West K W, Xie X C, and Lin X 2020 *Phys. Rev. Res.* **2** 022056
[39] Wang X B, Fu H L, Du L J, Liu X X, Wang P J, Pfeiffer L N, West K W, Du R R, and Lin X 2015 *Phys. Rev. B* **91** 115301
[40] Sun J, Niu J S, Li Y, Liu Y F, Pfeiffer L, West K, Wang P J, and Lin X 2022 *Fundam. Res.* **2** 178
[41] Samkharadze N, Schreiber K A, Gardner G C, Manfra M J, Fradkin E, and Csáthy G A 2016 *Nat. Phys.* **12** 191
[42] Schreiber K A, Samkharadze N, Gardner G C, Lyanda-Geller Y, Manfra M J, Pfeiffer L N, West K W, and Csáthy G A 2018 *Nat. Commun.* **9** 2400
[43] Huang K, Wang P J, Pfeiffer L N, West K W, Baldwin K W, Liu Y, and Lin X 2019 *Phys. Rev. Lett.* **123** 206602
[44] Hutson A and White D L 1962 *J. Appl. Phys.* **33** 40
[45] Bierbaum P 1972 *Appl. Phys. Lett.* **21** 595
[46] Wu M M, Liu X, Wang R F, Lin X, and Liu Y 2024 arXiv:2311.01718 [physics.app-ph]
[47] Zhao L L, Lin W L, Chung Y J, Baldwin K W, Pfeiffer L N, and Liu Y 2022 *Chin. Phys. Lett.* **39** 097301
[48] Recently, Wu *et al.* [32] revealed an interesting discovery: a noticeable modulation in the SAW velocity appears when varying current through the 2DES.