Eliminating the channel resistance in two-dimensional systems using viscous charge flow

2D Materials

PERSPECTIVE

Eliminating the channel resistance in two-dimensional systems using viscous charge flow

Wenhao Huang[1,2,6], Tathagata Paul[1,6,*], Mickael L Perrin[1,3,4,*] and Michel Calame[1,2,5,*]

[1] Empa, Swiss Federal Laboratories for Materials Science and Technology, Transport at Nanoscale Interfaces Laboratory, Überlandstrasse 129, CH-8600 Dübendorf, Switzerland
[2] Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
[3] Department of Information Technology and Electrical Engineering, ETH Zürich, 8092 Zurich, Switzerland
[4] Quantum Center, ETH Zürich, 8093 Zürich, Switzerland
[5] Swiss Nanoscience Institute, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland
[6] Equal contribution.
[*] Authors to whom any correspondence should be addressed.

E-mail: tathagata.paul@empa.ch, mickael.perrin@ee.ethz.ch and michel.calame@empa.ch

Keywords: graphene, hydrodynamic effects, scattering mechanisms, channel resistance reduction

OPEN ACCESS

RECEIVED
31 January 2024

REVISED
11 March 2024

ACCEPTED FOR PUBLICATION
12 April 2024

PUBLISHED
23 April 2024

Abstract

Driven by the pursuit of high-performance electronic devices and the exploration of quantum phenomena, research into two-dimensional (2D) systems and materials, has unveiled their exceptional properties and potential applications. While extensive efforts have centered on minimizing contact resistance, reducing the intrinsic channel resistance within the conducting material remains a formidable challenge. Research in this direction has focused on investigating superconductivity and ballistic transport. However, the practical applications of these phenomena are usually constrained by the requirement for cryogenic conditions. Charge transport in the hydrodynamic regime emerges as a versatile alternative, offering enhanced resilience to these challenges, and making it a promising avenue for effectively reducing channel resistance in 2D systems. The current perspective delves into charge hydrodynamics, exploring its mechanisms, recent advancements, enduring challenges, and its potential in reducing the channel resistance.

1. Introduction

1.1. Low resistance systems in two-dimensions

Channel resistance in bulk and two-dimensional (2D) systems can be reduced in certain conditions, when transport phenomena take place at extremes of the interaction spectrum for charges. At the non-interacting end of the spectrum lies ballistic transport. This phenomenon is observed in ultra-clean channels of bulk and 2D systems when all relevant interaction length scales for charges are larger than the device dimensions. Ballistic transport is characterized by the scattering-free transport of charges within the channel, resulting in minimal resistance. Alternatively, strong attractive interactions between charges can lead to the formation of Cooper pairs, resulting in superconductivity or charge transport with zero resistance. This remarkable macroscopic quantum phenomenon is observed in bulk systems [1] as well as 2D materials such as $NbSe_2$ [2–4] and bilayer graphene at a specific twist angle [5–7], and is driven by quantum coherence, holding the promise of dissipation-free current transport and more energy-efficient electronics. However, both these transport mechanisms have limitations. An optimal functionality of ballistic transport is contingent upon constant channel dimensions, presenting a challenge in practical applications where these dimensions vary [8, 9]. Superconductivity is generally observed at cryogenic temperatures, sometimes also requiring high pressure.

In response to these challenges, hydrodynamic transport emerges as a versatile alternative for reducing channel resistance with enhanced tolerance to variations in dimension. Furthermore, this transport regime remains viable at or near room temperature, presenting a promising avenue for practical applications [10–13].

1.2. Hydrodynamic transport

In the presence of strong interactions between charges, the independent electron approximation

breaks down and charge carriers, rather than behaving as isolated particles, exhibit collective motion akin to a viscous fluid. In this regime, the only dissipation mechanism is due to boundary scattering and, remarkably, an increasing interaction between charges leads to enhanced conductivity. This fascinating charge transport regime is referred to as hydrodynamic transport and possesses many analogies with classical fluid dynamics described by the Navier–Stokes equations [14–20] .

Central to this phenomenon are the scattering mechanisms that charge carriers encounter. These can be broadly classified into two groups, momentum-conserving and momentum-relaxing scattering processes. Non-Umklapp electron–electron (e–e) interactions characterized by an associated length-scale l_{ee} are momentum conserving. While individual electrons exchange momentum, the overall momentum of the system remains conserved. Momentum non-conserving scattering mechanisms on the other hand generally include electron–phonon (e–ph) interactions, scattering from lattice defects, and impurities. These interactions relax the momentum of electrons and in the process generate resistance to the flow of charges. In the current perspective, we assign the length scale l_{diff} for this ensemble of momentum-relaxing scattering processes. Hydrodynamic transport emerges when e–e interactions are responsible for the dominant scattering mechanism. In terms of scattering length scales, hydrodynamic transport corresponds to the condition $l_{ee} \ll l_{diff}, w$, where w is the smallest channel dimension. Meeting this requirement experimentally is challenging as it requires a balanced control of multiple physical parameters. At low temperatures, e–ph scattering is largely reduced, with the remaining momentum-relaxing scattering mechanism being the interaction between electrons and impurities. Using exceptionally clean materials, also these scattering events can be significantly suppressed. However, e–e interactions also tend to weaken with decreasing temperature. Finding a temperature regime where e–e interactions remain significant while avoiding e–ph scattering to play a predominant role is thus challenging. Engineering the different scattering length scales to solve this conundrum therefore requires additional tuning knobs beyond temperature. Several approaches can be envisioned. First, while e–ph interactions are determined by the lattice temperature, e–e scattering is mostly influenced by the electron temperature. An attractive approach would thus consist of disentangling these two, i.e. minimizing the lattice temperature while enhancing the electron temperature. Second, at any given temperature, the strength of the e–e scattering is affected by the carrier concentration in the channel, with higher charge carrier densities leading to a reduced e–e scattering [21]. Control over the charge carrier density can for example be achieved using an electrostatic gate. Overall, due this intricate interplay between different scattering mechanisms, satisfying the condition $l_{ee} \ll l_{diff}, w$ is challenging and, as a result, charge hydrodynamics has been an elusive phenomenon, with only few and mostly recent experimental observations being reported [21–26]. Since de Jong and Molenkamp observed one of the first evidence of electron hydrodynamic transport in high-mobility two-dimensional electron gases (2DEGs) [15], this relatively novel direction has witnessed substantial progress, spurred on by advancements in fabrication techniques and availability of high-quality crystals [17, 27–29]. Clearly, accessing this transport regime experimentally requires working with devices combining ultra-clean channel materials with precise control over both the lattice and electron temperature, as well as control over the charge carrier density. In this perspective, we briefly discuss specific experiments, current challenges, and potential future applications within the domain of hydrodynamic transport, with a specific focus on the reduction of channel resistance.

2. Hydrodynamic transport for reduced channel resistance

In ballistic devices, the Landauer–Sharvin (LS) resistance, R_{LS}, dominates transport and is inversely proportional to the number of conduction channels/modes (M) within the material:

$$R_{LS} = \frac{h}{2e^2}\frac{1}{M} \tag{1}$$

where h and e are the Planck constant and electronic charge, respectively. In a rectangular geometry, with a constant value of M inside the channel, R_{LS} remains the lowest attainable device resistance. However, one of the drawbacks of ballistic transport remains the sensitivity to channel geometry. Specifically, in device geometries with a varying value of M in the channel, ballistic transport no longer remains an efficient method of charge flow. This case arises for instance in a channel with constrictions [10, 30]. For ballistic systems, some of the transport modes originating at the source or the drain will be reflected at the constriction, see figure 1(a) top, leading to the channel resistance being limited by the constriction size. In the hydrodynamic regime, strong electronic interactions allow charge flow to naturally organize into streams with varying velocities, forming 'sheaths' of slower-moving fluid along the edges of the constriction. This cooperative behavior assists charge carriers in navigating the edges of the geometry, where electrons would otherwise lose their overall momentum (figure 1(a) bottom). This leads to a reduction of resistance below the LS limit and is commonly termed as superballistic transport. Superballistic transport has been reported in constrictions of graphene as well as 2DEGs [10, 30]. The authors of [30] report

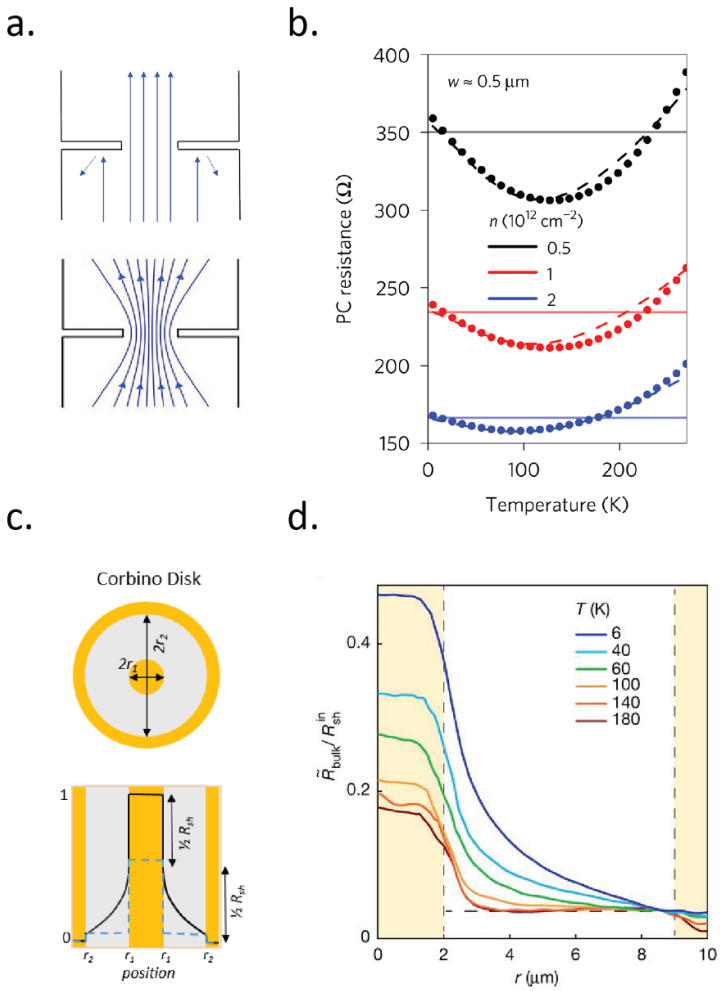

Figure 1. Hydrodynamic transport to eliminate channel resistance. (a) Top: Schematic of ballistic electronic flow in a point contact (PC), dashed lines indicate the reflected modes. Bottom: viscous electronic flow in a point contact. Adapted from [10], with permission from Springer Nature. (b) PC resistance for a 0.5 μm constriction at representative carrier densities. Dots: experimental data. Horizontal lines: ballistic resistance given by equation (1). Dashed curves: theoretical predictions for a viscous electron fluid. Adapted from [10], with permission from Springer Nature. (c) Spatial distribution of the Landauer Sharvin resistance in the Corbino Disk (Top Panel) geometry. The bottom panel shows the resistance as a function of position for ballistic (solid line) and hydrodynamic (dashed line) transport in the Corbino geometry. (d) The local bulk resistance, measured in a single-layer graphene Corbino disk is plotted as a function of channel position r for different values of temperature (T). The vanishing of the electric field in the bulk at elevated temperatures is indicative of hydrodynamic charge flow [31, 32]. Adapted from [12], with permission from Springer Nature.

that graphene constrictions in the hydrodynamic regime exhibit channel resistance (closed circles in figure 1(b)) that are below the expected ballistic resistance (solid lines in figure 1(b)). The deviations are even starker in the circular symmetric Corbino Disk (CD) geometry. In the CD geometry (figure 1(c)), the value of M (determined by the radii of the circle) varies continuously within the channel. For ballistic transport, R_{LS} is spread across the entire channel while hydrodynamic transport allows an almost complete elimination of R_{LS} in the channel region [13]. This effect has been experimentally verified in [12] using current flow imaging in a graphene CD geometry (figure 1(d)). The reduced channel resistance at elevated temperatures is indicative of a larger number of transport modes being accessible due to electronic interactions.

3. Challenges towards an exploitation of hydrodynamic charge transport

The hydrodynamic charge transport regime remains delicate to reach experimentally and poses experimental challenges which we discuss below.

3.1. Materials and nanofabrication

To make hydrodynamic transport viable for practical applications, it is imperative to expand its applicability up to room temperature. Achieving this necessitates the development of devices with specific attributes, including high mobility (i.e. very few moment-relaxing scattering events) and strong electronic interactions. 2DEGs [33, 34], bulk semimetals like WP_2 [20], MoP [35] and delafossites like $PdCoO_2$ [18] fulfill the criteria of charge

hydrodynamics at temperatures below 100 K. In these materials, e–ph scattering predominantly determines the transport at higher temperatures. To the best of our knowledge, graphene is currently the only material capable of demonstrating hydrodynamic transport near room temperature ($T > 150$ K). The specific reasons are threefold. First, the scattering of electrons with acoustic phonons is intrinsically weak [36] allowing for large diffusive mean free paths. Second, the e–e interaction strength is enhanced due to the 2D confinement effects and weaker mutual screening of charges in graphene when compared to metals [37, 38]. Third, advancements in fabrication techniques, including the use of hexagonal Boron Nitride (*h*-BN) encapsulation combined with edge contacts, allow for high-quality graphene-based device platforms. A combination of the above has led to several reports of hydrodynamic transport in single layer and bilayer graphene beyond 150 K [17, 21, 27–29].

It is interesting to note that, in this picture of a viscous charge flow in graphene, the extracted viscosities are larger than that of honey [16, 17], corresponding to a low Reynolds number (Re) regime and limiting charge transport to a laminar flow. Reaching a regime of operation in which a turbulent charge flow can take place would be extremely interesting from a fundamental point of view as well as from an application perspective. This would however require the discovery of new materials with stronger electronic interactions and lower viscosities, which represents a strong driver in the ongoing search for new materials that can meet these demanding requirements. In this regard, Kagome metals showing strong e–e interaction [39] emerge as promising candidates for future research.

3.2. Differentiating the hydrodynamic transport from ballistic transport

Hydrodynamic charge flow exhibits distinct properties, but distinguishing it from ballistic transport can be challenging due to shared transport signatures [32, 33, 40–45]. For instance, both ballistic and hydrodynamic transport can produce current vortices reminiscent of those in viscous flow [33, 46, 47]. Nevertheless, subtle differences can arise. For example, a double vortex state is predicted in the transition from a hydrodynamic regime to a laminar regime, while this state is absent in the ballistic to laminar regime transition [48]. Another challenge is that the parabolic current density characteristic of hydrodynamic charge flow can be replicated in ballistic transport [32]. In [32], the authors recommend measuring the local Hall field across the transport channel as an alternative to current density to differentiate between these transport regimes. Other methods typically involve considering the temperature and number density dependence of the relevant physical quantities. Ballistic transport tends to occur at low temperatures, while hydrodynamic transport is more likely to dominate at higher temperatures. Additionally, in contrast to ballistic transport, hydrodynamic charge flow is generally observed at intermediate number densities because, at higher number densities, e–e scattering is effectively screened. Distinguishing the hydrodynamic from the ballistic regime can be supported with computational techniques by modeling charge transport in both regimes, solving the Boltzmann transport equation in the measured device geometry [22, 27].

3.3. Boundary roughness

The interaction of charge carriers with device boundary plays an important role in hydrodynamic transport. Several signatures of hydrodynamic transport arising from the parabolic Poiseuille flow profile, like the Gurzhi effect [16] and geometry dependence of conductivity [16, 19], are sensitive to the details of the interaction between charges and boundaries, as quantified by the slip length. The current understanding of this parameter is however far from comprehensive [17, 49], and controlling the device boundaries is a formidable challenge that will need to be overcome to provide robust signatures of hydrodynamic behavior. The development of improved fabrication techniques is a very active area of interest, not only for charge hydrodynamics but also for the wider 2D materials research [50], and will certainly help reduce device-to-device variability and improve device boundaries control. Also, characterization techniques that can provide a direct measurement of the boundary slip length, such as transverse magnetic focusing, provide a very useful insight [34].

4. Outlook and potential application

4.1. Interconnection

Low resistance interconnects are essential for energy-efficient integrated circuits. In this regard, hydrodynamic charge transport has several benefits over other transport mechanisms. First, resistance in hydrodynamic charge flow is at most similar (rectangular devices) and mostly lower (CD or constriction geometries) than the Landauer Sharvin resistance. Second, hydrodynamic charge flow is robust against variations in channel geometry such as the reduction of the number of modes throughout the channel. Finally, hydrodynamic charge flow is generally observed at higher temperatures when compared to ballistic transport, making it more favorable for future applications. Materials with strong electronic interactions and weak e–ph and defect scattering, like graphene, are ideal candidates for low-resistance interconnects. With interconnects operating in the hydrodynamic regime promising efficient and reliable electron transport, their applications will range from high-speed data transmission to energy-efficient electronics, see figure 2.

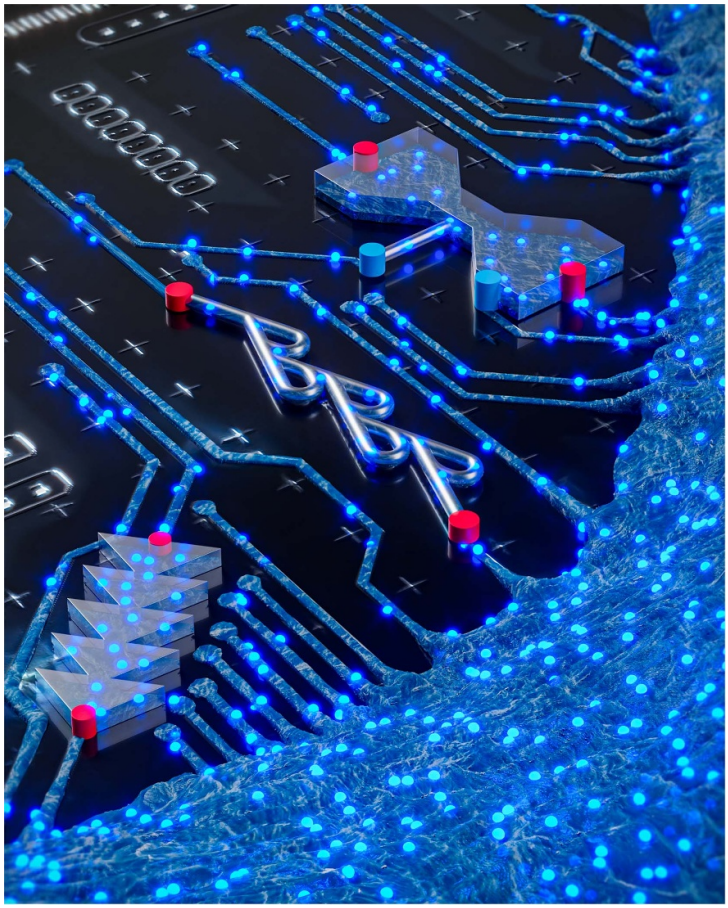

Figure 2. Hydrodynamic transport for future applications. Illustration of potential future applications of hydrodynamic electron flow: interconnects, rectifiers, and amplifiers operating within the hydrodynamic transport regime.

4.2. Others

Rectification using semiconductor diodes or switches has limited applicability when applied to high-frequency signals. Interestingly, rectification using charge hydrodynamics is predicted to be able to overcome this limitation. When Re is large, the convective term of the Navier–Stokes equation dominates. Combined with an appropriate device geometry, this can lead to a flow resistance that is direction-dependent and therefore rectification up to terahertz frequencies [51–53]. An example of such a geometry is the Tesla Valve (figure 2). In [54, 55], efforts were made to adapt this geometry for charge flow. However, the rectification ratio remains limited, primarily due to the low Re characterizing the electron fluid [16, 27, 56]. To enhance future applications, it is imperative to develop electron flow with higher Re, attainable with material systems demonstrating lower viscosity.

The nonlinearity of the Navier–Stokes equations allows for non-linear, beyond ohmic transport properties in the hydrodynamic regime. For example, a drag effect stemming from a focused stream of particles has the capacity to induce a charge current within a hydrodynamic system. This effect draws parallels to the Venturi effect, which arises from Bernoulli's equations. Initial demonstrations of this concept have been carried out in 2DEGs [57, 58]. The characteristic non-linearity in transport arising from particle–particle (e–e) interactions is not only useful for distinguishing hydrodynamic charge flow but also can be utilized for designing analog amplifiers (figure 2) [59].

5. Conclusion

Despite the increasing number of studies in this field, hydrodynamic transport remains a nascent area with numerous unanswered questions. A comprehensive understanding of the physical principles behind hydrodynamic effects, including in particular a deeper insight into the tuning of the various scattering mechanisms, remains a critical aspect for a successful experimental implementation of this transport regime. In addition, finding material systems with strong electronic interactions and high mobility, coupled with advancements in fabrication capabilities to reduce device-to-device variations is critical for exploring all the potential applications of hydrodynamic electronics. Several novel material systems are promising, with twisted 2D heterostructures being particularly attractive. Indeed, the combination

of geometric confinement and a high degree of control over the Moiré potential provided by twisted heterostructures allows for a large tunability of the electronic interactions, making 2D heterostructures ideal candidates for investigating charge hydrodynamics [5, 60]. We note that interaction-driven correlations can also lead to an insulating behavior in twisted devices, showing the need for a proper selection of charge density to tune the devices in the transport regime of interest [61, 62].

Data availability statement

No new data were created or analyzed in this study.

Acknowledgment

W H, T P, and M C gratefully acknowledge the Swiss National Science Foundation for financial support through the Sinergia Grant No. 189924 (Hydronics). M L P gratefully acknowledges the funding provided by the Swiss National Science Foundation under the Eccellenza Professorial Fellowship No. PCEFP2_203663 and the Swiss State Secretariat for Education, Research, and Innovation (SERI) under Contract Number MB22.00076. The authors extend their appreciation to the project partners of the SNF Sinergia grant Hydronics, Dr B Gotsmann, Prof. N Marzari, and Prof. I Zardo. The authors acknowledge fruitful discussions with Dr I Shorubalko and Prof. J J Heremans.

Conflict of interest

The authors declare that there are no competing interests.

ORCID iDs

Tathagata Paul https://orcid.org/0000-0003-3960-2095
Michel Calame https://orcid.org/0000-0001-7467-9915

References

[1] Durrell J H, Ainslie M D, Zhou D, Vanderbemden P, Bradshaw T, Speller S, Filipenko M and Cardwell D A 2018 *Supercond. Sci. Technol.* **31** 103501
[2] Frindt R 1972 *Phys. Rev. Lett.* **28** 299
[3] Wang H *et al* 2017 *Nat. Commun.* **8** 394
[4] Wickramaratne D, Khmelevskyi S, Agterberg D F and Mazin I 2020 *Phys. Rev.* X **10** 041003
[5] Cao Y, Fatemi V, Fang S, Watanabe K, Taniguchi T, Kaxiras E and Jarillo-Herrero P 2018 *Nature* **556** 43
[6] Oh M, Nuckolls K P, Wong D, Lee R L, Liu X, Watanabe K, Taniguchi T and Yazdani A 2021 *Nature* **600** 240
[7] Park J M, Cao Y, Watanabe K, Taniguchi T and Jarillo-Herrero P 2021 *Nature* **590** 249
[8] Mayorov A S *et al* 2011 *Nano Lett.* **11** 2396
[9] Ella L *et al* 2019 *Nat. Nanotechnol.* **14** 480
[10] Krishna Kumar R *et al* 2017 *Nat. Phys.* **13** 1182
[11] Guo H, Ilseven E, Falkovich G and Levitov L S 2017 *Proc. Natl Acad. Sci.* **114** 3068
[12] Kumar C *et al* 2022 *Nature* **609** 276
[13] Stern A, Scaffidi T, Reuven O, Kumar C, Birkbeck J and Ilani S 2022 *Phys. Rev. Lett.* **129** 157701
[14] Gurzhi R 1963 *J Exp. Theor. Phys.* **17** 521
[15] De Jong M and Molenkamp L 1995 *Phys. Rev.* B **51** 13389
[16] Huang W, Paul T, Watanabe K, Taniguchi T, Perrin M L and Calame M 2023 *Phys. Rev. Res.* **5** 023075
[17] Bandurin D *et al* 2016 *Science* **351** 1055
[18] Moll P J, Kushwaha P, Nandi N, Schmidt B and Mackenzie A P 2016 *Science* **351** 1061
[19] Keser A C *et al* 2021 *Phys. Rev.* X **11** 031030
[20] Gooth J, Menges F, Kumar N, Süß V, Shekhar C, Sun Y, Drechsler U, Zierold R, Felser C and Gotsmann B 2018 *Nat. Commun.* **9** 4093
[21] Ho D Y, Yudhistira I, Chakraborty N and Adam S 2018 *Phys. Rev.* B **97** 121404
[22] Varnavides G, Yacoby A, Felser C and Narang P 2023 *Nat. Rev. Mater.* **8** 726–41
[23] Narozhny B N and Gornyi I V 2021 *Front. Phys.* **9** 640649
[24] Lucas A and Fong K C 2018 *J. Phys.: Condens. Matter* **30** 053001
[25] Narozhny B, Gornyi I and Titov M 2021 *Phys. Rev.* B **103** 115402
[26] Narozhny B N 2022 *Riv. Nuovo Cimento* **45** 661
[27] Torre I, Tomadin A, Geim A K and Polini M 2015 *Phys. Rev.* B **92** 165433
[28] Ku M J, Zhou T X, Li Q, Shin Y J, Shi J K, Burch C, Anderson L E, Pierce A T, Xie Y and Hamo A 2020 *Nature* **583** 537
[29] Danz S and Narozhny B N 2020 *2D Mater.* **7** 035001
[30] Ginzburg L V, Gold C, Röösli M P, Reichl C, Berl M, Wegscheider W, Ihn T and Ensslin K 2021 *Phys. Rev. Res.* **3** 023033
[31] Jenkins A, Baumann S, Zhou H, Meynell S A, Daipeng Y, Watanabe K, Taniguchi T, Lucas A, Young A F and Jayich A C B 2022 *Phys. Rev. Lett.* **129** 087701
[32] Sulpizio J A *et al* 2019 *Nature* **576** 75
[33] Gupta A, Heremans J, Kataria G, Chandra M, Fallahi S, Gardner G and Manfra M 2021 *Phys. Rev. Lett.* **126** 076803
[34] Gupta A, Heremans J J, Kataria G, Chandra M, Fallahi S, Gardner G C and Manfra M J 2021 *Nat. Commun.* **12** 5048
[35] Kumar N *et al* 2019 *Nat. Commun.* **10** 2475
[36] Adam S, Brouwer P W and Sarma S D 2009 *Phys. Rev.* B **79** 201404
[37] Oka T, Tajima S, Ebisuoka R, Hirahara T, Watanabe K, Taniguchi T and Yagi R 2019 *Phys. Rev.* B **99** 035440
[38] Roldán R, López-Sancho M P and Guinea F 2008 *Phys. Rev.* B **77** 115410
[39] Di Sante D, Erdmenger J, Greiter M, Matthaiakakis I, Meyer R, Fernández D R, Thomale R, van Loon E and Wehling T 2020 *Nat. Commun.* **11** 3997
[40] Chandra M, Kataria G, Sahdev D and Sundararaman R 2019 *Phys. Rev.* B **99** 165409
[41] Bandurin D A, Shytov A V, Levitov L S, Kumar R K, Berdyugin A I, Ben Shalom M, Grigorieva I V, Geim A K and Falkovich G 2018 *Nat. Commun.* **9** 4533
[42] Braem B A *et al* 2018 *Phys. Rev.* B **98** 241304
[43] Shytov A, Kong J F, Falkovich G and Levitov L 2018 *Phys. Rev. Lett.* **121** 176805
[44] Holder T, Queiroz R, Scaffidi T, Silberstein N, Rozen A, Sulpizio J A, Ella L, Ilani S and Stern A 2019 *Phys. Rev.* B **100** 245305
[45] Nazaryan K G and Levitov L 2021 Robustness of vorticity in electron fluids (arXiv:2111.09878)
[46] Pellegrino F M, Torre I, Geim A K and Polini M 2016 *Phys. Rev.* B **94** 155414
[47] Lent C S 1990 *Appl. Phys. Lett.* **57** 1678
[48] Aharon-Steinberg A *et al* 2022 *Nature* **607** 74
[49] Aharon-Steinberg A, Marguerite A, Perello D J, Bagani K, Holder T, Myasoedov Y, Levitov L S, Geim A K and Zeldov E 2021 *Nature* **593** 528

[50] Lanza M, Smets Q, Huyghebaert C and Li L-J 2020 *Nat. Commun.* **11** 5689
[51] Tao R, Ng T, Su Y and Li Z 2020 *Phys. Fluids* **32** 052010
[52] Di Carlo D, Irimia D, Tompkins R G and Toner M 2007 *Proc. Natl Acad. Sci.* **104** 18892
[53] Vyšniauskas J, Lisauskas A, Bauer M, Čibiraitė D, Matukas J and Roskos H G 2017 *J. Phys.: Conf. Ser.* **906** 012023
[54] Gungor A C, Koepfli S M, Baumann M, Ibili H, Smajic J and Leuthold J 2022 *Materials* **15** 4141
[55] Geurs J, Kim Y, Watanabe K, Taniguchi T, Moon P, and Smet J H 2020 Rectification by hydrodynamic flow in an encapsulated graphene tesla valve (arXiv:2008.04862 [cond-mat.mes-hall])
[56] Principi A, Vignale G, Carrega M and Polini M 2016 *Phys. Rev.* B **93** 125410
[57] Taubert D, Schinner G, Tranitz H, Wegscheider W, Tomaras C, Kehrein S and Ludwig S 2010 *Phys. Rev.* B **82** 161416
[58] Taubert D, Schinner G J, Tomaras C, Tranitz H-P, Wegscheider W and Ludwig S 2011 *J. Appl. Phys.* **109** 102412
[59] Hui A, Oganesyan V and Kim E-A 2021 *Phys. Rev.* B **103** 235152
[60] Cao Y, Luo J, Fatemi V, Fang S, Sanchez-Yamagishi J, Watanabe K, Taniguchi T, Kaxiras E and Jarillo-Herrero P 2016 *Phys. Rev. Lett.* **117** 116804
[61] Cao Y *et al* 2018 *Nature* **556** 80
[62] Chen G *et al* 2019 *Nat. Phys.* **15** 237