Anisotropic band flattening in graphene with one-dimensional superlattices

Yuta Li1, Scott Dietrich1,6, Carlos Forsythe1,7, Takashi Taniguchi2, Kenji Watanabe2, Pilkyung Moon3,4,5 and Cory R. Dean1✉

Patterning graphene with a spatially periodic potential provides a powerful means to modify its electronic properties. In particular, in twisted bilayers, coupling to the resulting moiré superlattice yields an isolated flat band that hosts correlated many-body phases. However, both the symmetry and strength of the effective moiré potential are constrained by the constituent crystals, limiting its tunability. Here, we have exploited the technique of dielectric patterning to subject graphene to a one-dimensional electrostatic superlattice (SL). We observed the emergence of multiple Dirac cones and found evidence that with increasing SL potential the main and satellite Dirac cones are sequentially flattened in the direction parallel to the SL basis vector, behaviour resulting from the interaction between the one-dimensional SL electric potential and the massless Dirac fermions hosted by graphene. Our results demonstrate the ability to induce tunable anisotropy in high-mobility two-dimensional materials, a long-sought property for novel electronic and optical applications. Moreover, these findings offer a new approach to engineering flat energy bands where electron interactions can lead to emergent properties.

Two-dimensional (2D) materials such as graphene and the transition metal dichalcogenides exhibit a wide range of electronic and optical properties, making them ideal platforms for exploring fundamental phenomena and promising building blocks for next-generation devices. Imposing SL structures on 2D materials has proven to be a powerful technique to gain further control over the opto-electronic response in these materials. In the case of graphene, this has enabled the realization of a variety of new phenomena not inherent in the native material, including additional Dirac cones, superconductivity, Mott-like insulating states and the appearance of ferromagnetic ordering and topologically non-trivial sub-bands. Patterning graphene with a one-dimensional (1D) SL, where the electric potential varies periodically along one axis only, is expected to yield a highly anisotropic energy–momentum relation between the directions perpendicular and parallel to the SL basis vector. At certain, well-defined, strengths of SL modulation, the group velocity of charge carriers at the Dirac cone can become renormalized to zero in the direction perpendicular to the SL basis vector, leading to a ‘flattened’ Dirac cone in one direction, while the Fermi velocity in the other direction remains unaffected. The induced anisotropy is theoretically anticipated to yield new electronic properties, but nevertheless, experimental studies have been limited and inconclusive. For example, new resistive features appearing at finite carrier density, \( n \), have been reported in 1D SL-patterned graphene. However, the physical origin of these resistance oscillations has been attributed to both Fabry–Pérot interference and band structure modifications. Moreover, the direct observation of transport anisotropy, a key signature expected for scattering from the 1D SL, has not been experimentally demonstrated.

In this study, we exploited the technique of dielectric patterning to fabricate high-mobility graphene devices with a gate-tunable 1D SL. A typical device construction employed in our study is shown in Fig. 1a–c (see Methods for details). By measuring the transport response with current applied both parallel and perpendicular to the SL, we have identified a relative hierarchy of band flattenings between multiple Dirac points (DPs), in excellent agreement with band structure modelling. Our results demonstrate that 1D SLs can be used to dynamically induce extreme anisotropy in the graphene band structure.

Figure 1d–f shows \( R_{xx} \) and \( R_{xy} \), that is, the resistance measured with current flowing parallel and perpendicular to the direction of the 1D SL basis vector, respectively, versus the carrier density from a device with SL period \( L = 47 \ \text{nm} \), measured for three different strengths of the SL modulation. In each case, the density was varied by tuning the top gate, \( V_{tg} \), while maintaining a fixed bias on the bottom SL gate, \( V_s \). For all three values of SL bias, \( V_s \), the resistance measured in the y-direction resembles the typical response observed in unpatterned graphene, namely a single resistance peak centred at the charge neutrality point (CNP). At temperature \( T = 2 \ \text{K} \), the width of the CNP peak measures \( 2 \times 10^3 \ \text{cm}^{-2} \), which is similar to the typical values measured for hBN-encapsulated graphene devices with no SL patterning. Additionally, with the top gate biased to give a carrier density of \( n = 10^2 \ \text{cm}^{-2} \) and the SL potential tuned to zero, we measured a carrier mobility of \( \mu = 130,000 \ \text{cm}^2 \ \text{V}^{-1} \ \text{s}^{-1} \) (Supplementary Information 2). This corresponds to a mean free path of \( \sim 1.5 \mu \), similar to the device width of 2 \( \mu \) and an order of magnitude longer than the SL periodicity. Both metrics indicate that the SL patterning has not substantially degraded the mobility in graphene.

In the \( xx \) direction, the responses are dramatically different for each \( V_{sl} \). At \( V_{sl} = 21 \ \text{V} \), in addition to a peak in \( R_{xx} \) at the CNP, two additional resistance peaks appear that are located symmetrically about the CNP peak (Fig. 1d). Upon increasing the SL gate bias to \( V_{sl} = 44 \ \text{V} \), the satellite resistance peaks grow, becoming more prominent than the CNP peak, and simultaneously shift to larger carrier density (Fig. 1e). At \( V_{sl} = 88 \ \text{V} \), the CNP becomes a resistance peak.
Fig. 1 | Transport anisotropy in graphene subjected to a 1D superlattice. a, Cartoon schematic showing the architecture of our 1D patterned dielectric superlattice graphene device structure. The SL potential arises due to patterning of the dielectric layer that separates the doped silicon substrate from the hexagonal boron nitride (hBN)-encapsulated graphene device (see text). MLG, monolayer graphene; FLG, few-layer graphene b, Optical image of a 1D SL graphene device with period \( L = 47 \) nm. Scale bar, 5 \( \mu \)m. c, Schematic diagram of the L-shaped Hall bar, defining \( V_{xx} \) and \( V_{yy} \). The diagram is not drawn to scale. Green region, graphene channel; yellow region, metal-to-graphene edge contacts. The parallel black lines represent the 1D SL lines etched onto SiO\(_2\), with the line spacing greatly exaggerated. d-f, Resistance measurements in the \( L = 47 \) nm 1D SL device at three different strengths of SL modulation.

Fig. 2 | Band structure calculations for an \( L = 55 \) nm graphene 1D SL system. The strength of SL modulation is quantified by \( u = \frac{V_0 L}{\hbar v_F} \), a dimensionless quantity. a, Calculated band structure of a 1D SL graphene system with \( u = 4\pi \). b, Contour plots of the first conduction band showing the main DP (\( k_y = 0 \)) and the first satellite DPs (\( k_y \neq 0 \)) for \( u = 2\pi \), \( 4\pi \) and \( 6\pi \). c, Normalized Fermi velocity in the \( y \) direction at the \( l \)th Dirac cone, \(|f_l| = |v_y/v_F|\), as a function of SL modulation \( u \). For example, the main DP (\( l = 0 \)) becomes flat in the \( k_y \) direction at \( u = 4\pi \), and the first satellite DPs (\( l = 1 \)) become flat in the \( k_y \) direction at \( u = 6\pi \). The inset shows the band structure slice at \( k_y = 0 \).
minimum and four distinct peaks are located symmetrically about the CNP (Fig. 1f). The strong asymmetry between the xx and yy responses confirms that the 1D SL preferentially modifies the electron transport in the direction of the 1D SL wave vector. The evolution of the $R_{xx}$ features with increasing $V_{SL}$, that is, the satellite resistance features varying in number, carrier density and relative magnitude, is distinctly different from the case of graphene subjected to a 2D SL modulation$^6$, where by contrast the satellite resistive peaks increases with increasing SL bias, evolving from a single maximum at the CNP for all values of $V_{SL}$, measured in an $L = 55$ nm device. At the same time, the first satellite Dirac cones retain linear dispersion in the $k_y$ direction (but not in the $k_x$ direction) when the SL potential $u$ satisfies

$$u = \begin{cases} 
4\pi N & \text{even } l, \text{ including } l = 0 \\
4\pi N + 2\pi & \text{odd } l 
\end{cases}$$

for every positive integer $N$, but excluding $u = 2\pi l$ (Fig. 2c and also Supplementary Information 3).

Figure 3a,c shows the experimentally measured $R_{xx}$ and $R_{yy}$ plotted versus SL bias, $V_{SL}$, and average carrier density, $n$, for a device with SL period $L = 55$ nm. The $R_{xx}$ response exhibits a elaborate scale-like pattern of resistive maxima and minima: the number of resistive peaks increases with increasing SL bias, evolving from a single maximum at the CNP $V_{SL} = 0$ V to five resolved maxima at $V_{SL} \approx 40$ V ($u \approx 2\pi$). Figure 3b,d shows theoretical plots of $R_{xx}$ and $R_{yy}$ versus the dimensionless SL potential, $u$, and density, $n$, calculated from the band structure shown in Fig. 2 by using a
We observe excellent agreement between the measured and calculated resistance in the same device. In Fig. 3a,b, the dashed white lines trace the relation \( R_{\text{xx}} = (\lambda - 0.23) \times 10^2 \Omega \), were obtained by averaging the measured resistance over a small density window of \( (6.53 \pm 0.23) \times 10^{12} \text{ cm}^{-2} \). The numbers indicate the filling fractions associated with the main or satellite fans.

Fig. 4 | Magnetotransport in a 1D SL device. a. Measured longitudinal resistance, \( R_{\text{xx}} \), as a function of carrier density, \( n \), and magnetic field, \( B \), in an \( L = 47 \text{ nm} \) device with \( V_\text{bi} = 48 \text{ V} \). The red arrows indicate the density locations where the satellite Landau fans converge. b. \( R_{\text{yy}} \) as a function of \( n \) and \( B \) measured in the same device. In a and b, the dashed white lines trace the relation \( 2c = (\lambda - 0.23) \), where \( r_c \) is the cyclotron radius, given by \( h / \sqrt{2m^*}eB \) (\( e \) is the elementary charge), and \( \lambda \) is an integer (see text). c. Fan-tracing diagram highlighting traces of \( R_{\text{xx}} \) minima in Fig. 4a. The \( R_{\text{xx}} \) minima features associated with the main (satellite) Dirac point are coloured in black (red). The numbers indicate the filling fractions associated with the main or satellite fans. d. \( R_{\text{yy}} \) and \( R_{\text{xx}} \) as a function of magnetic field, \( B \), for carrier density \( n = 6.53 \times 10^2 \text{ cm}^{-2} \). The dashed lines indicate the magnetic field at which the corresponding oscillation is theoretically expected (see text). To suppress quantum Hall oscillations and highlight the commensurability oscillations, the plotted curves were obtained by averaging the measured resistance over a small density window of \( (6.53 \pm 0.23) \times 10^{12} \text{ cm}^{-2} \) (Supplementary Information 8).

Relaxation time approximation (Supplementary information 3). We observe excellent agreement between the measured and calculated resistance in both the xx and yy directions.

The dashed lines in Fig. 3a,b trace features associated with the main and satellite Dirac cones as \( V_\text{bi} \) increases from 0 V (corresponding to \( \nu = 0 \)) to 90 V (corresponding to \( \nu \approx 7\pi \)). Along the CNP peak trajectory \( (n = 0) \), both \( R_{\text{xx}} \) and \( R_{\text{yy}} \) are high due to the low density of states at the main DP, similarly to what is observed in unpatterned graphene. At \( \nu = 4\pi \), however, \( R_{\text{yy}} \) exhibits a local maximum, while \( R_{\text{xx}} \) simultaneously shows a minimum (labelled ‘A’ in Fig. 3a,c). This is in agreement with the calculated response shown in Fig. 3b,d and provides strong evidence for the picture of the band flattening of the primary Dirac cone with \( \nu = 4\pi \) representing an extremum, as indicated in Fig. 2c. The increase in resistance \( R_{\text{yy}} \) results from flattening of the main Dirac cone along the y direction (Eq. (1)) with the Fermi velocity, \( \nu_y \), reducing towards zero. On the other hand, this band flattening increases the integrated density of states near the CNP. Thus, even though the Fermi velocity in the x direction, \( \nu_x \), remains unchanged, the overall increased density of states results in a decreased \( R_{\text{xx}} \). Interestingly, however, the \( R_{\text{yy}} \) local maximum and \( R_{\text{xx}} \) minimum vanish as \( \nu \) increases further, manifesting the unflattening of the primary Dirac cone.

Similar cycles of \( R_{\text{xx}} \) maxima/minima were also observed for the finite energy satellite Dirac cones \( (n \neq 0) \). In Fig. 3a, along the dashed line tracing the evolution of \( R_{\text{xx}} \) associated with the first satellite DP, there appears a resistance maximum at \( \nu = 4\pi \) and a minimum at \( \nu = 6\pi \) (labelled ‘B’). The \( R_{\text{xx}} \) maximum at \( \nu = 4\pi \) corresponds to the appearance of the unflattened first satellite Dirac cone, that is, low density of states (Fig. 3g), while the \( R_{\text{xx}} \) minimum at \( \nu = 6\pi \) (inset labelled ‘B’ in Fig. 3i) results from this first satellite Dirac cone flattening in the \( k_y \) direction, increasing the overall density of states. The first satellite Dirac cone is again unflattened as \( \nu \) increases further. This non-monotonic behaviour of \( R_{\text{xx}} \) is thus a result of cyclic flattening/unflattening of the first satellite Dirac cone.
as the strength of SL modulation increases, similar to the behaviour observed in $R_{xx}$ near the main DP. We note further that the $u$ values at which $R_{xx}$ of the main and the first satellite DPs show maxima/ minima agree with the calculated Fermi velocity variation shown in Fig. 2c. At finite density, the $R_{xx}$ response is largely featureless (Fig. 3c). This is because, at the energies of the 8th satellite DP ($l \neq 0$), there are plenty of other states with $v_{\perp} \approx 0$ at finite $k_y$ (see the band structure contours in Fig. 2b), which provide extra transport channels in the $y$ direction.

Finally, we examined the magnetotransport properties of our graphene 1D SL devices. Figure 4a,b shows the longitudinal resistances, $R_{xx}$ and $R_{yy}$ respectively, as a function of carrier density, $n$, and applied magnetic field, $B$, for an $L = 47$ nm device. In these measurements, $V_{sd} = 48$ V, corresponding to $u \approx \pi$. $R_{xx}$ (Fig. 4a) versus the magnetic field shows a Landau fan of integer quantum Hall states emanating from the CNP at $n = 0$ with filling factors identical to those of pristine graphene ($\nu = 4n + 2$, where $N$ is an integer). In addition, two satellite fan-like features are also visible, emanating from $n = \pm 2.7 \times 10^{11}$ cm$^{-2}$ (Fig. 4a, red arrows), the carrier densities at which satellite Dirac cones emerge, as predicted by band structure simulation in Fig. 3b. $R_{xx}$ minima features emanating from the $n = -2.7 \times 10^{11}$ cm$^{-2}$ satellite fan are indicated in the fan-tracing diagram shown in Fig. 4c (Supplementary Information 7). We take this as further confirmation that the zero-field satellite $R_{xx}$ peaks in our measurement reflect changes in graphene band structure and the formation of satellite Dirac points, and are not Fabry–Pérot resonance. The plot of $R_{xx}$ versus magnetic field (Fig. 4b) shows a similar overall trend to $R_{xx}$, however, we note that $R_{xx}$ is about two orders of magnitude larger than $R_{xx}$, as the carrier wavefunction under magnetic field is localized along the $x$ direction, leading to a high $R_{xx}$ (Supplementary Information 6). Both $R_{xx}$ and $R_{yy}$ show an overall resistance modulation, evolving along curved trajectories that follow a $B \propto \sqrt{n}$ relation (dashed white lines in Fig. 4a,b). We interpret these features as commensurability oscillations (Fig. 4d)\(^{11,13}\). In the semiclassical picture, the overall $R_{xx}$ resistance is expected to be $1/B$ periodic, with resistance minima appearing whenever the cyclotron diameter matches the periodicity of the SL, that is, when $2r_c$ satisfies

$$2r_c = \left( \frac{\lambda - 1}{2} \right) L$$

where $\lambda$ is an integer\(^{11,13}\) and $L$ is the lattice period. The locations of the minima in our $R_{xx}$ data show excellent agreement with Eq. (2), consistent with the results previously reported by Drienovsky et al.\(^{11}\). Alternatively, commensurability oscillations can be understood quantum mechanically by a $1/B$ periodic oscillation in the Landau level bandwidth, which reaches zero when Eq. (2) is satisfied. We note that the commensurability oscillations along the two measured directions appear out of phase such that when $R_{xx}$ fades, $R_{yy}$ grows, and vice versa\(^{11}\), providing further confirmation that the 1D SL imparts an asymmetric distortion of the band structure (Supplementary Information 6).

In summary, we have presented a full characterization of transport anisotropy in a graphene 1D SL system. Our devices were found to host a multitude of band structure features, including satellite Dirac points, anisotropic flattened Dirac points and side Dirac points (Supplementary Discussion S3) at the charge neutrality point, the last two features not having been found in the 2D systems engineered with 2D SLs studied so far. The 1D SL gate acts as a powerful 1D SL gate acts as a powerful

devices\(^{13}\) and with full tunability of the anisotropy. This paves the way for the development of novel device technologies that exploit the unusual transport, optical and thermoelectric properties of anisotropic 2D materials, but without the limitations of naturally occurring materials\(^8\). Patterned 2D systems beyond graphene using a periodic 1D SL\(^{13,15}\) could lead to new opportunities by coupling anisotropic band structures to properties not inherent in graphene, such as strong spin–orbit coupling and magnetic ordering.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-021-00849-9.

Received: 15 June 2020; Accepted: 7 January 2021;
Published online: 15 February 2021

References
1. Park, C. H., Yang, L., Son, Y. W., Cohen, M. L. & Louie, S. G. Anisotropic behaviours of massless Dirac fermions in graphene under periodic potentials. Nat. Phys. 4, 213–217 (2008).
2. Park, C. H., Son, Y. W., Yang, L., Cohen, M. L. & Louie, S. G. Landau levels and quantum Hall effect in graphene superlattices. Phys. Rev. Lett. 103, 046808 (2009).
3. Brey, L. & Fertig, H. A. Emerging zero modes for graphene in a periodic potential. Phys. Rev. Lett. 103, 046809 (2009).
4. Cao, Y. et al. Unconventional superconductivity in magic-angle graphene superlattices. Nature 556, 43–50 (2018).
5. Cao, Y. et al. Correlated insulator behaviour at half-filling in magic-angle graphene superlattices. Nature 556, 80–84 (2018).
6. Fornyhe, C. et al. Band structure engineering of 2D materials using patterned dielectric superlattices. Nat. Nanotechnol. 13, 566–571 (2018).
7. Xia, F., Wang, H., Hwang, J. C. M., Neto, A. H. C. & Yang, L. Black phosphorus and its isoelectronic materials. Nat. Rev. Phys. 1, 306–317 (2019).
8. Tian, H. et al. Low-symmetry two-dimensional materials for electronic and photonic applications. Nano Today 11, 763–777 (2016).
9. Shi, L. K., Ma, I. & Song, J. C. W. Gate-tunable flat bands in van der Waals patterned dielectric superlattices. 2D Mater. 7, 015028 (2019).
10. Geim, A. K. & Novoselov, K. S. The rise of graphene. Nature Mater. 6, 183–191 (2007).
11. Novoselov, K. S., Mishchenko, A., Carvalho, A. & Neto, A. H. C. 2D materials and van der Waals heterostructures. Science 353, 969–973 (2016).
12. Yankowitz, M. et al. Emergence of superlattice Dirac points in graphene on hexagonal boron nitride. Nat. Phys. 8, 382–386 (2012).
13. Ponomarenko, L. A. et al. Cloning of Dirac fermions in graphene superlattices. Nature 497, 594–597 (2013).
14. Hunt, B. et al. Massive Dirac fermions and Hofstadter butterfly in a van der Waals heterostructure. Science 340, 1427–1430 (2013).
15. Dean, C. R. et al. Hofstadter’s butterfly and the fractal quantum Hall effect in moiré superlattices. Nature 497, 598–602 (2013).
16. Yankowitz, M. et al. Tuning superconductivity in twisted bilayer graphene. Science 363, 1059–1064 (2019).
17. Sharpe, A. L. et al. Emergent ferromagnetism near three–quarters filling in twisted bilayer graphene. Science 365, 605–608 (2019).
18. Serlin, M. et al. Intrinsic quantized anomalous Hall effect in a moiré heterostructure. Science 367, 900–903 (2020).
19. Barbier, M., Vasiilopoulos, P. & Peeters, F. M. Extra Dirac points in the energy spectrum for superlattices on single-layer graphene. Phys. Rev. B 81, 075438 (2010).
20. Dubey, S. et al. Tunable superlattice in graphene to control the number of Dirac points. Nano Lett. 13, 3990–3995 (2013).
21. Drienovsky, M. et al. Towards superlattices: lateral bipolar multibarriers in graphene. Phys. Rev. B 89, 115421 (2014).
22. Drienovsky, M. et al. Few-layer graphene patterned bottom gates for van der Waals heterostructures. Preprint at https://arxiv.org/abs/1703.05631 (2017).
23. Drienovsky, M. et al. Commensurability oscillations in one-dimensional graphene superlattices. Phys. Rev. Lett. 121, 026806 (2018).
24. Kuiri, M., Gupta, G. K., Ronen, Y., Das, T. & Das, A. Large Landau-level splitting in a tunable one-dimensional graphene superlattice probed by magneto-capacitance measurements. Phys. Rev. B 98, 035418 (2018).
25. Dean, C. R. et al. Boron nitride substrates for high-quality graphene electronics. Nat. Nanotechnol. 5, 722–726 (2010).
26. Allen, P. B. in Quantum Theory of Real Materials (eds Chelikowsky, J. R. & Louie, S. G.) viii, 549 (Kluwer Academic Publishers, 1996).
27. Madsen, G. K. H. & Singh, D. J. BoltzTraP: A code for calculating band-structure dependent quantities. Comput. Phys. Commun. 175, 67–71 (2006).
28. Shore, K. A. Introduction to graphene-based nanomaterials: from electronic structure to quantum transport. Contemp. Phys. 55, 344–345 (2014).
29. Weiss, D., Vonklitzing, K., Ploog, K. & Weimann, G. Magnetoresistance oscillations in a two-dimensional electron gas induced by a submicrometer periodic potential. Europhys. Lett. 8, 179–184 (1989).
30. Gerhardts, R. R., Weiss, D. & Vonklitzing, K. Novel magnetoresistance oscillations in a periodically modulated two-dimensional electron gas. Phys. Rev. Lett. 62, 1173–1176 (1989).
31. Beenakker, C. W. J. Guiding-center-drift resonance in a periodically modulated two-dimensional electron gas. Phys. Rev. Lett. 62, 2020–2023 (1989).
32. Endo, A. & Iye, Y. Measurement of anisotropic transport using unidirectional lateral superlattice with square geometry. J. Phys. Soc. Jpn. 71, 2067–2068 (2002).
33. Qiao, J. S., Kong, X. H., Hu, Z. X., Yang, F. & Ji, W. High-mobility transport anisotropy and linear dichroism in few-layer black phosphorus. Nat. Commun. 5, 4473 (2014).
34. Wu, S., Killi, M. & Paramekanti, A. Graphene under spatially varying external potentials: Landau levels, magnetotransport, and topological modes. Phys. Rev. B 85, 195404 (2012).
35. Xu, H. et al. Oscillating edge states in one-dimensional MoS2 nanowires. Nat. Commun. 7, 12904 (2016).

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
© The Author(s), under exclusive licence to Springer Nature Limited 2021
Methods
Our 1D SLs were fabricated by plasma etching of SiO$_2$ using a thin poly(methylmethacrylate) (PMMA) mask. We applied 495 A$^2$ PMMA, spun to a thickness of 50 nm, onto a doped silicon wafer supporting thermally grown SiO$_2$ of thickness 285 nm. Superlattice line patterns were written as an array of lines with current $i = 300–400$ pA using the Nanobeam nB4 at Columbia University. Holes were plasma-etched using an Oxford Plasmalab 80 Plus system with a mixture of CHF$_3$ and argon gas at flow rates of 40 and 5 sccm, respectively, to a depth of 40–50 nm. The 1D SLs were then cleaned using O$_2$ plasma followed by piranha etching. Afterwards, graphene–hBN stacks were mechanically transferred onto the 1D SLs using polypropylene carbonate (PPC) slides. These stacks were fabricated into L-shaped double Hall bar devices using standard electron-beam lithography processes. Transport measurements were taken in a 9T Janis $^4$He cryostat in the temperature range $T = 1.5–2$ K. Voltage measurements were carried out using SR830 lock-in amplifiers at a current bias of 90–100 nA. For more detailed information on device fabrication, see Supplementary Information 1.

Data availability
Presented measurement data are available from the corresponding author upon reasonable request.

Code availability
The computer code for calculating band structures and simulating $R_{xx}$ and $R_{yy}$ values is available from the corresponding author upon reasonable request.

Acknowledgements
This research was supported primarily by the Office of Naval Research (ONR) Young Investigators Program (no. N00014-17-1-2832). P.M. was supported by the Science and Technology Commission of Shanghai Municipality (grant no. 19ZR1436400) and NYU–ESNU Institute of Physics at NYU Shanghai. This research was carried out using the High Performance Computing resources at NYU Shanghai.

Author contributions
Y.L., P.M. and C.R.D. conceived the experiment. Y.L. fabricated the samples, performed transport measurements and analysed transport data. P.M. provided theoretical modelling of the system and helped interpret transport data. S.D. and C.F. performed preliminary studies on a van der Pauw sample. Y.L., P.M. and C.R.D. co-wrote the paper. K.W. and T.T. provided hBN material for device fabrication.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41565-021-00849-9.

Correspondence and requests for materials should be addressed to C.R.D.

Peer review information Nature Nanotechnology thanks the anonymous reviewers for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.