Towards chirality control of graphene nanoribbons embedded in hexagonal boron nitride

Hui Shan Wang\(^1,2,3,15\), Lingxiu Chen\(^1,3,15\), Kenan Elibol\(^4,5,15\), Li He\(^6,15\), Haomin Wang\(^1,2,3\), Chen Chen\(^1,2,3\), Chengxin Jiang\(^1,3,7\), Chen Li\(^8,9\), Tianru Wu\(^1,3\), Chun Xiao Cong\(^10\), Timothy J. Pennycook\(^4,5\), Giacomo Argentero\(^4\), Daoli Zhang\(^6,9\), Kenji Watanabe\(^11\), Takashi Taniguchi\(^11\), Wenyai Wei\(^12,13\), Qinghong Yuan\(^12,13\), Jannik C. Meyer\(^6,14,15\) and Xiaoming Xie\(^1,2,3,7\)

The integrated in-plane growth of graphene nanoribbons (GNRs) and hexagonal boron nitride (h-BN) could provide a promising route to achieve integrated circuitry of atomic thickness. However, fabrication of edge-specific GNRs in the lattice of h-BN still remains a significant challenge. Here we developed a two-step growth method and successfully achieved sub-5-nm-wide zigzag and armchair GNRs embedded in h-BN. Further transport measurements reveal that the sub-7-nm-wide zigzag GNRs exhibit sub-5-nm-wide zigzag GNRs, while narrow armchair GNRs exhibit some fluctuation in the bandgap-width relationship. An obvious conductance peak is observed in the transfer curves of 8- to 10-nm-wide zigzag GNRs, while it is absent in most armchair GNRs. Zigzag GNRs exhibit a small magnetic conductance, while armchair GNRs have much higher magnetic conductance values. This integrated lateral growth of edge-specific GNRs in h-BN provides a promising route to achieve intricate nanoscale circuits.

Scanning transmission electron microscopy (STEM) investigation shows that in-plane epitaxy was realized at the boundary of graphene and h-BN with controlled chirality at the edge along the GNR while developed laterally. Further electrical investigation reveals that all narrow ZGNRs exhibit a bandgap larger than 0.4 eV while narrow AGNRs exhibit a relatively large variation in bandgap. Transistors made of GNRs with large bandgaps exhibit on/off ratios of more than 10^5 at room temperature with carrier mobilities higher than 1,500 cm^2 V^{-1} s^{-1}. With such a method, narrow GNRs along high-symmetry lattice orientations and with smooth edges in h-BN provide exciting possibilities for designer electronics and fundamental research in condensed matter physics.

Figure 1a depicts the structure of ZGNR and AGNR embedded in a h-BN lattice layer. Recent theoretical work predicts that ZGNRs embedded in h-BN exhibit strong current polarization because of their asymmetrical edges\(^23\), while all the AGNRs are semiconductors\(^24\). There have been several attempts to grow graphene ribbons via plasma enhanced chemical vapour deposition (CVD)\(^24\) or thermal CVD\(^25\). Because of the difficulties in fabrication, little experimental work on chirality-controllable GNRs embedded in h-BN has been reported.

Figure 1b schematically illustrates the synthesis of oriented GNRs in h-BN via a two-step method (materially graphically cutting and template growth). A single-crystalline h-BN layer exhibits...
most likely due to lattice distortions caused by mismatched lattice constants and coefficients of thermal expansion between graphene and h-BN. The tiny out-of-plane distortions exclude the possibility of the formation of multilayered GNRs. Similarly, Fig. 2c,d gives the AFM height images of an ultra-narrow AC nano-trench obtained via Pt particle-assisted etching and an ultra-narrow AGNR, respectively. The corresponding AFM friction images of the ZGNR and AGNR are given in Supplementary Fig. 8. The circle insets show the atomic-resolution friction images of h-BN, which confirm that the crystallographic orientations of the trench/GNR are along the ZZ direction in Fig. 2a,b and the AC lattice direction in Fig. 2c,d.

We also tried to image the step-edges of h-BN trenches. Atomic-resolution analysis on the h-BN edge of a ZZ-oriented trench and AC-oriented trench is given in Supplementary Figs. 9 and 10, respectively. As shown in these figures, both edges are atomically smooth.

Because of the size limitation of the AFM tips, the depth of our sub-5-nm-wide trenches could not be exactly determined, but these trenches were reasonably judged to also be monolayered, based on the measurements of wider nano-trenches (Extended Data Fig. 2d), which could be obtained by using large etching particles. The depth of the h-BN nano-trench is ~340 pm, which indicates that the wider trench is only monolayer (more discussion in Supplementary Text and Supplementary Tables 1 and 2).

To study the crystallinity of the embedded GNRs, we investigate here freely suspended thin h-BN flakes embedded with GNRs, using transmission electron microscopy (TEM) and STEM. Low electron energies (80 keV for TEM and 60 keV for STEM) were used to minimize radiation damage. For overview images (Extended Data Fig. 2i), we found that the contrast of adsorbed contamination could be almost completely eliminated by calculating a difference between a medium-angle annular dark-field (MAADF) image and a high-angle annular dark-field (HAADF) image: MAADF – α × HAADF, where α is adjusted to minimize the visibility of contamination, and thereby reveal the ribbons or other features of interest already at low magnification.

Extended Data Fig. 2j is a MAADF – α × HAADF image showing an area with an embedded ZGNR. The bright white particles observed are primarily silicon oxide. The white dashed box in Extended Data Fig. 2i shows the position of a ZGNR (a dark line). The MAADF image of Extended Data Fig. 2j shows a zoomed-in view of the ZGNR field in Extended Data Fig. 2i. As shown in Extended Data Fig. 2j, the ZGNR is straight and uniform at the nanometre scale, and the measured width is ~3.2 nm (within the accuracy of the STEM measurements). The h-BN–GNR boundaries are sharp and highly crystalline. The length of the GNR observed in Extended Data Fig. 2j is more than 80 nm. The seamless construction of the GNR is mainly attributed to the gaseous catalytic growth. Extended Data Fig. 2k shows a Wiener-filtered MAADF image of the region inside the dashed frame in Extended Data Fig. 2j. The GNR is clearly along the ZZ direction of the h-BN lattice, indicating that the embedded GNR is ZZ lattice oriented. It is also clear that the whole lattice is connected in a continuous hexagonal network. Due to contamination from hydrocarbon, it is difficult to distinguish carbon, boron and nitrogen atoms via electron energy loss spectroscopy mapping. However, the boundaries between GNR and h-BN still can be distinguished straightforwardly in Extended Data Fig. 2j. In this area, the h-BN flake has a thickness of about 3–5 layers, and the GNRs exhibit obvious contrast to the surrounding h-BN region (Supplementary Fig. 11). From the atomic-resolution image in Extended Data Fig. 2k, it is clear that the ZGNR is in lattice coherence with the h-BN. Details about the fabrication of the TEM/STEM samples are given in the Methods section and Supplementary Fig. 11. The sample was imaged via TEM in advance. As shown in Supplementary Fig. 11, a TEM dark-field (DF) image clearly shows the presence of graphene in the

**Fig. 1 | Synthetic strategy of oriented GNRs embedded in h-BN.**

**a.** Sketch of ZGNR and AGNR embedded in h-BN. **b.** Synthetic strategy to orient GNRs with crystallographic edge orientations. Different particles cut nano-trenches with different edge topologies in a h-BN layer. The edge-specific nano-trenches are used to define the growth and the dimensions of GNRs along the ZZ (top) or AC (bottom) direction.
AFM investigation confirms that both ZGNR embedded in h-BN are given in Supplementary Figs. 13 and 14. The high-resolution carried out to investigate the boundaries of GNR–h-BN. The results crystalline and have a lattice coherence with the top layer of h-BN. Atomic-resolution STEM images show that the GNRs are highly from opposite sides of the trenches coalesced into a complete GNR. Finally, the GNRs developed on the h-BN and developed laterally. Formally, the GNRs developed at nanometre-scale resolution, and has a width of ~5.3 nm.

The h-BN–GNR heterostructure is highly crystalline and has lattice coherence. Extended Data Fig. 3j, from which the lattice orientation of the AGNR is determined.

Similarly, the embedded AGNRs are also investigated by STEM/TEM. Extended Data Fig. 3i,j show MAADF images of a small portion of the suspended h-BN layers embedded with AGNRs. The white arrow in Extended Data Fig. 3i points to a GNR oriented along the AC direction. To the lower left of the AGNR appear two parallel ZGNRs roughly perpendicular to the AC one. Note that the suspended h-BN flake buckled a little in the field of view. In Extended Data Fig. 3j, we see a close-up view of the AGNR embedded in the few-layered h-BN sheet. The AGNR is straight and uniform at nanometre-scale resolution, and has a width of ~5.3 nm. The h-BN–GNR heterostructure is highly crystalline and has lattice coherence. Extended Data Fig. 3k is the Fourier transform of the image shown in Extended Data Fig. 3j, from which the lattice orientation of the AGNR is determined.

GNRs grew via a step-flow mechanism from two step-edges of the h-BN top-layer trench59. The orientation of the graphene edge can be modified via tuning ethyne and silane flow in the CVD process59. GNRs grew along the atomic step-edge of the top layer on the h-BN and developed laterally. Finally, the GNRs developed from opposite sides of the trenches coalesced into a complete GNR. Atomic-resolution STEM images show that the GNRs are highly crystalline and have a lattice coherence with the top layer of h-BN.

A high-resolution noncontact AFM (nc-AFM) measurement was carried out to investigate the boundaries of GNR–h-BN. The results are given in Supplementary Figs. 13 and 14. The high-resolution AFM investigation confirms that both ZGNR embedded in h-BN and AGNR embedded in h-BN indeed have atomically smooth edges within tens of nanometres.

Field-effect transistors (FETs) were fabricated to investigate the electrical properties of the GNRs. An ~5 nm-wide AGNR (Supplementary Fig. 15) was fabricated into a FET with a channel length (L) of ~278 nm (sample no. A39). Its conductance G versus back-gate voltage (Vgate) at different temperatures is shown in Fig. 3a, and exhibits obvious modulations with respect to Vgate. Its field-effect carrier mobility μ = Vgate/L at 300 K is about 1,700 cm² V⁻¹ s⁻¹, where the effective capacitance Cgate = 3.71 pF m⁻¹. Figure 3b shows the temperature dependence of the resistance under different Vgate values. The bandgap (Eg) extracted by fitting the resistance–temperature curve is 183 ± 19 meV according to the simple two-band (STB) model (details of the STB model are in the Supplementary Text), where both thermal activation and contact resistance have been taken into account. Another sub-5 nm-wide AGNR FET (Supplementary Fig. 16) measured exhibits a relatively high on/off ratio in conductance. As shown in Fig. 3c, the AGNR device (sample no. A187) in a channel length of ~236 nm exhibited Ggate/Gdrain > 10⁵ at 300 K. Figure 3d shows the Ith-Vg characteristics of the AGNR device recorded at T = 300 K under Vgate values from ~25 to 25 V (Ith-Vg curves at T = 100 K in Supplementary Fig. 17a). The Ith-Vg curves under all Vgate values are almost linear before Ith saturates at both 300 K and 100 K. This indicates that the Pd–GNR contact resistance is small or absent, and the main reason may be that Pd has a high work function and good wetting interactions with GNRs13,52. The extracted bandgap value using the STB model is ~531 meV, and the field-effect mobility is ~1,428 cm² V⁻¹ s⁻¹. The scattering mean free path (MFP) was estimated to be ~79 nm as...
the relatively high $G = 1.8 e^2/h$ at 300 K when $V_{\text{gate}} = -25$ V, where $e$ is the charge of an electron and $h$ is the Planck constant.

Similarly, the electronic transport properties of a typical sub-5-nm-wide ZGNR FET (sample no. Z143) were measured (Supplementary Fig. 18), and their bandgap/carrier mobility/MFP were also extracted. Obviously, the narrow ZGNRs exhibit a bandgap $>0.4$ eV. The bandgap extracted as a function of the corresponding ribbon width for all narrow GNRs is plotted in Fig. 3e. As shown in Fig. 3e, the bandgap scaled inversely with ribbon width for both ZGNRs and AGNRs. The width dependence of the bandgap for ZGNRs fits well with the function $E_g \approx \alpha/w$, where $E_g$ is in units of eV and $w$ is in units of nm, and where parameter $\alpha \approx 1.89$ eV nm. Similarly, the fitting parameter $\beta \approx 2.44$ eV nm for AGNRs. All of them display obvious semiconducting characteristics. For the narrow ZGNRs, the narrower the ribbon, the higher the bandgap. The gap opening in the ZGNRs embedded in h-BN is attributed to the combined influence from $e-e$ interactions, uniaxial strain and the stacking order on h-BN. For the narrow AGNR, the bandgap does not scale monotonically with ribbon width, and there is some fluctuation on the bandgap scaling. According to first-principles DFT cal-
The field-effect properties of AGNRs of widths ranging from 8 to 10 nm. The GNR devices can be classified into four types according to their electronic transport characteristics (Supplementary Figs. 19–21). The statistics of GNRs of different types are shown in Fig. 4c. All ZGNRs exhibit a clear peak in their transfer curves, while ~87.2% of AGNRs are classified as Type IV AGNRs whose conductance peaks disappear at high temperature. In the pie chart of AGNRs, Type I indicates AGNRs whose transfer curves are missing the conductance peaks (a typical example is no. A135), and Type IV indicates AGNRs whose transfer curves are of a tiny peak at low temperature. The normalized MC of all GNRs measured as a function of gate values at 4 K; the magnetic field was applied perpendicular to substrate plane (z direction). Normalized MC of sample no. A135 measured at different gate values at 2 K with the magnetic field perpendicular to the substrate. Distribution of normalized MC of all GNRs measured as a function of gate values at 4 K; the magnetic field was applied perpendicular to substrate plane (z direction).

The field-effect properties of the edge-specific GNRs of widths of 8 to 10 nm were systematically investigated. Figure 4a shows $G$ versus $V_{\text{gate}}$ at different temperatures for a typical ZGNR device (sample no. Z196) with a channel length of ~261 nm and a width of ~9.5 nm. The peak remains almost unchanged in conductance even when the temperature increases to 275 K. This weak metallic behaviour of conductance indicates that the peak position may exhibit electronic states. Figure 4b shows the relationship of conductance as a function of $V_{\text{gate}}$ with temperature for a typical AGNR FET (sample no. A135) with a channel length of ~261 nm and a width of ~9.5 nm. Unlike the ZGNR, the AGNR device does not exhibit an obvious conductance peak near its charge neutrality point. As shown in Fig. 4b, its conductance exhibited a drastic V- or U-shape drop with respect to $V_{\text{gate}}$. This phenomenon suggests a bandgap opening in the nanoribbon.

In total, we measured the electronic properties of 36 ZGNRs and 39 AGNRs whose widths ranged from 8 to 10 nm. The GNR devices can be classified into four types according to their electronic transport characteristics (Supplementary Figs. 19–21). The statistics of GNRs of different types are shown in Fig. 4c. All ZGNRs exhibit a clear peak in their transfer curves, while ~87.2% of AGNRs are missing the peaks in their transfer curves. The conductance peak of ~80.6% of ZGNRs can survive at 275 K. The conductance peak is believed to be related to the density of states at the ZZ edges of graphene.

Magneto-transport properties of the relatively wide GNRs were also investigated. Figure 4d shows the relationship of normalized magnetic conductance (MC) versus magnetic field $B$ with $V_{\text{gate}}$ in a ZGNR (sample no. Z196). The MC curves are normalized by using the mobility values of the narrow GNRs at $V_{\text{gate}}$ = -15 V.
ΔG/Gₐ = (G(B) – Gₛ)/Gₛ, where G(B) represents conductance measured at a magnetic field of B and Gₛ is the conductance measured in the absence of a magnetic field. A magnetic response of only <10% is observed at certain Vₚₑₑ values. Similar measurements were performed with an AGNR (sample no. A135). As shown in Fig. 4e, a large positive MC of 7,000% (Vₚₑₑ = 0 V) is found at 2 K. The values of the MC are positive at all Vₚₑₑ values and can be readily tuned by Vₚₑₑ. A saturation trend for MC at all Vₚₑₑ values is also seen in Fig. 4e (more MC results are shown in Supplementary Figs. 22–27). The normalized MCs of all GNRs obtained under 9 T at different Vₚₑₑ values are plotted in Fig. 4f. As shown in Fig. 4f, MCs of all the ZGNRs are positive but less than 10%, while almost all of the AGNRs exhibit a positive MC much higher than 10%.

GNRs with rough edges are fabricated for comparison. Their fabrication processes, morphologies and transport properties are shown in Supplementary Figs. 28–34. Information about metal residue on GNRs is given in Supplementary Figs. 35–38.

The experimental results clearly show that the ZGNRs exhibit relatively small MC values while AGNRs have larger MC values. It is believed that the mechanism for the MC is related to the GNRs’ chirality. Further experiments and theoretical studies will be carried out to understand the mechanism responsible for the MC behaviour in the edge-specific GNRs.

This work reports a strategic process for the fabrication of specific GNRs in the top atomic layer of insulating h-BN. The process combines traditional top-down (crystallographic cutting of a h-BN layer) and bottom-up (GNR template growth) approaches together. The process allows for the growth of electrically isolated components (GNRs) in continuous two-dimensional insulating h-BN sheets with seamless in-plane heterojunctions ensuring that the components retain distinct electronic properties. The components do not alter the nature of the h-BN base as far as the mechanical strength, flexibility and optical transparency, which is desired in flexible, transparent electronics. Electrical transport measurement shows that ZGNRs and AGNRs exhibit obvious differences in their transfer curves and magnetic conductance. The integrated growth of semi-conducting GNRs on high-quality insulating substrates provides the fundamental building blocks of atomically thin ultra-large-scale integration circuitry. Beyond fabrication, ZGNRs in contact with a superconductor are predicted to exhibit a topological electronic state that might have applications in quantum computing.

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/s41563-020-00806-2.

Received: 3 October 2019; Accepted: 19 August 2020; Published online: 21 September 2020

References
1. Son, Y.-W., Cohen, M. L. & Louie, S. G. Half-metallic graphene nanoribbons. Nature 444, 347–349 (2006).
2. Llinas, J. P. et al. Short-channel field-effect transistors with 9-atom and 13-atom wide graphene nanoribbons. Nat. Commun. 8, 633 (2017).
3. Baringhaus, J. et al. Exceptional ballistic transport in epitaxial graphene nanoribbons. Nature 506, 349–354 (2014).
4. Nakada, K., Fujita, M., Dresselhaus, G. & Dresselhaus, M. S. Edge state in graphene ribbons: nanometer size effect and edge shape dependence. Phys. Rev. B 54, 17954–17961 (1996).
5. Magda, G. Z. et al. Room-temperature magnetic order on zigzag edges of narrow graphene nanoribbons. Nature 514, 608–611 (2014).
6. Ruffieux, P. et al. On-surface synthesis of graphene nanoribbons with zigzag edge topology. Nature 531, 489–492 (2016).
7. Yang, L., Park, C.-H., Son, Y.-W., Cohen, M. L. & Louie, S. G. Quasiparticle energies and band gaps in graphene nanoribbons. Phys. Rev. Lett. 99, 186801 (2007).
8. Son, Y.-W., Cohen, M. L. & Louie, S. G. Energy gaps in graphene nanoribbons. Phys. Rev. Lett. 97, 216803 (2006).
9. Jia, X. et al. Graphene edges: a review of their fabrication and characterization. Nanoscale 3, 86–95 (2011).
10. Wassmann, T. et al. Structure, stability, edge states, and aromaticity of graphene ribbons. Phys. Rev. Lett. 101, 096402 (2008).
11. Seiitosen, A. P. et al. Structure and stability of graphene nanoribbons in oxygen, carbon dioxide, water, and ammonia. Phys. Rev. B 82, 115425 (2010).
12. Jia, X. et al. Controlled formation of sharp zigzag and armchair edges in graphitic nanoribbons. Science 323, 1701–1705 (2009).
13. Girir, C. O. et al. Graphene at the edge: stability and dynamics. Science 323, 1705–1708 (2009).
14. Kim, K. et al. Atomically perfect torn graphene edges and their reversible reconstruction. Nat. Commun. 4, 2723 (2013).
15. Geim, A. K. & Grigorieva, I. V. Van der Waals heterostructures. Nature 499, 419–425 (2013).
16. Novoselov, K. S., Mishchenko, A., Carvalho, A. & Castro Neto, A. H. 2D materials and van der Waals heterostructures. Science 335, 564–569 (2011).
17. Ci, L. et al. Atomic layers of hybridized boron nitride and graphene domains. Nat. Mater. 9, 430–435 (2010).
18. Liu, L. et al. Heteropitaxial growth of two-dimensional hexagonal boron nitride templated by graphene edges. Science 343, 163–167 (2014).
19. Levandorf, M. P. et al. Graphene and boron nitride lateral heterostructures for atomically thin circuitry. Nature 488, 627–632 (2012).
20. Liu, Z. et al. In-plane heterostructures of graphene and hexagonal boron nitride with controlled domain sizes. Nat. Nanotechnol. 8, 119–124 (2013).
21. Gong, Y. J. et al. Direct chemical conversion of graphene to boron- and nitrogen- and carbon-containing atomic layers. Nat. Commun. 5, 3193 (2014).
22. Li, K. & Zhang, X.-H. Asymmetrical edges induced strong current-polarization in embedded graphene nanoribbons. Phys. Lett. A 382, 1167–1170 (2018).
23. Ding, Y., Wang, Y. & Ni, J. Electronic properties of graphene nanoribbons embedded in boron nitride sheets. Appl. Phys. Lett. 95, 123105 (2009).
24. Lu, X. et al. Graphene nanoribbons epitaxy on boron nitride. Appl. Phys. Lett. 108, 113103 (2016).
25. Chen, L. et al. Edge control of graphene domains grown on hexagonal boron nitride. Nanoscale 9, 11475–11479 (2017).
26. Tang, S. et al. Silane-catalysed fast growth of large single-crystalline graphene on hexagonal boron nitride. Nat. Commun. 6, 4999 (2015).
27. Mashoff, T. et al. Bistability and oscillatory motion of natural nanomembranes appearing within monolayer graphene on silicon dioxide. Nano Lett. 10, 461–465 (2010).
28. Susi, T. et al. Isotope analysis in the transmission electron microscope. Nat. Commun. 7, 13040 (2016).
29. Hawkes, P. W. Advances in Imaging and Electron Physics Vol. 138 (Elsevier, 2005).
30. Chen, L. et al. Oriented graphene nanoribbons embedded in hexagonal boron nitride trenches. Nat. Commun. 8, 14703 (2017).
31. Javey, A., Guo, J., Wang, Q., Lundstrom, M. & Dai, H. Ballistic carbon nanotube field-effect transistors. Nature 424, 654–657 (2003).
32. Mann, D., Javey, A., Kong, J., Wang, Q. & Dai, H. Ballistic transport in metallic nanotubes with reliable Pd ohmic contacts. Nano Lett. 3, 1541–1544 (2003).
33. Pereira, V. M., Neto, A. H. C. & Peres, N. M. R. Tight-binding approach to uniaxial strain in graphene. Phys. Rev. B 80, 045401 (2009).
34. Hunt, B. et al. Massive Dirac fermions and Hofstadter butterfly in a van der Waals heterostructure. Science 340, 1427–1430 (2013).
35. Wu, S. et al. Magnetotransport properties of graphene nanoribbons with zigzag edges. Phys. Rev. Lett. 120, 216601 (2018).
36. Rizzo, D. J. et al. Topological band engineering of graphene nanoribbons. Nature 560, 204–208 (2018).
37. Heimes, A., Koteles, P. & Schön, G. Majorana fermions from Shiba states in an antiferromagnetic chain on top of a superconductor. Phys. Rev. B 90, 060507 (2014).
Methods

Etching process on h-BN. First, the h-BN flakes were mechanically exfoliated on quartz substrates. The substrates were then annealed at 650 °C in an O₂ flow for 60 min and a subsequent Ar/H₂ flow for another 60 min to clean the surface of the h-BN. Next, a NiCl₂ solution of 0.1 mg ml⁻¹ was spun at 4,000 r.p.m. for 100 s onto the substrate. The substrates were then baked for 10 min on a hot plate. Then samples coated with NiCl₂ were submitted to a two-step process: annealing at 1,100 °C for 30 min under an Ar/H₂ flow (102 sccm) and etching at 1,200 °C for 30–60 min under an Ar/H₂ flow (850:150 sccm). The etching pressure was found to be ~130 Pa. The samples with H₃PO₄ were annealed at 1,150 °C for 30 min, and then kept at 1,300 °C for 10–30 min in an Ar/H₂ flow (30:10 sccm) under a pressure of ~7 Pa. After etching, the system was cooled in the protection of an argon flow (Supplementary Fig. 1).

GaN growth. After nano-trenches were fabricated in h-BN, the quartz substrates with h-BN flakes were subjected to ultrasonic bathing in an HCl solution, deionized water and acetone, in sequence. Subsequently, the quartz substrates were loaded into a furnace and heated to 1,280 °C in an argon flow, and after that, a C₂H₂ flow and a mixture of silane/argon (5% mole ratio of silane) were introduced into the chamber for GaN growth. The ratio of C₂H₂ to silane was optimized for AGNR and ZGNR growth. The pressure was kept at ~2 Pa during ZGNR growth and ~1 Pa during AGNR growth, and the typical time for growth was 2 min. After growth, the substrates were cooled in the protection of an argon flow (Supplementary Fig. 3).

The h-BN flakes with ultra-narrow GNRS were transferred onto a silicon substrate capped with 300 nm of SiO₂ for further transport measurement.

AFM. Both h-BN nano-trenches and GNRS samples were characterized by AFM (Dimension Icon, Bruker) in contact mode, while the atomic-resolution images were obtained by another AFM (Multimode IV, Veeco) under ambient conditions. The AFM images were all recorded in contact mode using SNL—10 AFM tips from Bruker that possess a nominal tip radius of less than 10 nm. For atomic-resolution scanning, the force constant k of the cantilever tips was in the range of 0.05–0.5 N m⁻¹, and the scan rate was set to a value in the range of 60–100 Hz to reduce the noise from thermal drift. To obtain a high accuracy, several hours of pre-scanning were carried out to warm up the sample and ensure high imaging stability, and scanners with a travel range of less than 10 μm in the x and y directions were used.

Raman spectroscopy characterization. Raman spectra were obtained with a WITec micro-Raman instrument (mode Alpha 300 R) possessing excitation laser lines of 532 nm. The results are shown in Supplementary Fig. 39. An objective lens with ×100 magnification and a 0.95 numerical aperture was used, producing a laser spot of ~500 nm in diameter. The laser power was kept at less than 1 mW on the sample surface to avoid laser-induced heating.

Computational details of thermodynamic simulation for h-BN edges and GNR growth. The calculation was performed within the framework of DFT as implemented in the Vienna Ab initio Simulation Package. The electronic exchange and correlation were included through the generalized gradient approximation in the Perdew–Burke–Ernzerhof form. The interaction between valence electrons and ion cores was described by the projected augmented wave method, and the energy cut-off for the plane wave functions was 400 eV. All structures were optimized by a conjugate-gradient method until the energy converged to 1.0 eV per atom. The climbing image nudged-elastic band method was utilized to search for further TEM investigation, we cleaved h-BN flakes grown with GNRs onto the heterostructure are freely suspended on holes measuring approximately ~1 μm in diameter.

STEM measurements. Initial characterization was performed in a Philips CM200 microscope operated at 80 kV. Selected samples were characterized at high resolution using an aberration-corrected Nion UltraSTEM100 operated at 60 kV. These samples were annealed via radiative or laser-induced heating before STEM measurements to reduce the contaminant on the surface. Note that it is extremely challenging to obtain completely clean surfaces in the GNR areas even after multiple-round annealing treatments. Practically, contamination like hydrocarbon impurities may be directly absorbed from the atmosphere onto the sample surface. The contamination can move and accumulate at energetically favoured areas (for example, wrinkles, grain boundaries and defects) during the annealing treatments. In addition, mobile contamination may be pinned into place by the electron beam. The contamination makes atomic-level characterization of the GNR–h-BN interface by electron microscopy and electron energy loss spectroscopy very difficult.

Device fabrication and electrical measurements. GNRS transistors were fabricated by a standard electron-beam lithographic technique with 20 nm Pd as source/drain contacts. The thickness of h-BN flakes transferred onto a Si substrate with a 300 nm SiO₂ capping layer is normally in a range from 15 to 35 nm. The devices were then annealed in a hydrogen flow at 200 °C for 1 h to improve the contact quality. The electrical transport was measured in a physical property measurement system (Quantum Design) at a pressure of ~1 × 10⁻⁶ torr via a Keithley 4200.

Data availability

The data represented in Figs. 3 and 4 are provided with the paper as source data. All other data that support results in this Article are available from the corresponding authors on reasonable request. Source data are provided with this paper.

Acknowledgements

H.W. and X.X. thank J.H. Edgar (Kansas State University, USA) for supplying the partial h-BN crystals. H. S. Wang, L. Chen and H. Wang thank M. Liu, X. Qiu and J. Pan from NCNT of China, F. Liu, H. Tsai, M. Crommie from UC Berkeley, USA, J. Xue and P. Yu from ShanghaiTech University and S. Wang from SUT for AFM measurement. H. S. Wang, L. Sun and H. Wang thank B. Sun and S. Li from Harbin University for the fusion of the STEM image and the electron energy loss spectroscopy mapping images. Funding: The work was partially supported by the National Key R&D program (Grant No. 2017YFF0206106), the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB30000000), the National Science Foundation of China (Grant Nos. 15171317, 51302096, 61774980, 91964102), the Science and Technology Commission of Shanghai Municipality (Grant Nos. 16ZR144270, 16ZR1402500, 18511110700), Shanghai Rising-Star Program (A type) (Grant No.18QG1404800), the Hubei Provincial Natural Science Foundation of China (Grant No. ZRM2017000370), China Postdoctoral Science Foundation (Grant No. 2017M621563, 2018T110415), and the Fundamental Research Funds of Wuhan City (No. 201606010100017). C.L. acknowledges support from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 656738 – Interfacial Reactions. T.J.P. acknowledges funding from European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement no. –655760 — DIGIPHASE. K.W. and T.T. acknowledge support from the Elemental Strategy Initiative conducted by the MEXT, Japan and the CREST (JPMJCR15F5), JST, C.L.C. acknowledges financial support from the National Young 1000 Talent Plan of China and the National Key R&D Program of China (No. 2018YFA0703700). L.H. acknowledges financial support from the programme of China Scholarships Council (No. 201760160037).

Author contributions

H.W. and X.X. directed the research work. H.W. conceived and designed the research. L.H.W., L. Chen and C.C. performed the growth experiments for the GNRS. L.C., C.C., C.J. and H.S.W. performed the AFM measurements. H.S.W. fabricated the electronic devices and performed the transport measurements. C.C.X. performed the Raman measurements. K.E., C.L., T.J.P., G.A. and J.C.M. carried out the STM measurements. K.W. and T.T. fabricated the h-BN crystals. W.W. and Q.Y. performed the thermodynamic simulation for h-BN edges and GNR growth. H.W., H.S.W., L.C., J.C.M., K.E., L.H. and C.C.X. analysed the experimental data and contributed to critical discussions of the manuscript. The authors declare no competing interests.

Additional information

Extended data is available for this article at https://doi.org/10.1038/s41563-020-00806-2. Supplementary information is available for this paper at https://doi.org/10.1038/s41563-020-00806-2.

Correspondence and requests for materials should be addressed to H.W. or J.C.M. Reprints and permissions information is available at www.nature.com/reprints.
Extended Data Fig. 1 | AFM investigation on h-BN nano-trenches obtained via nickel and platinum nanoparticle etching. a, AFM friction image of zigzag oriented trenches produced by nickel particles. The trenches exhibit about -30°, 30° or 90° with respect to h-BN wrinkles which are armchair oriented. The green dash line represents a trench orientation while the white dash line denotes a wrinkle orientation. Inset is a zoom-in view of the selected region in-lattice-resolution, confirming that the trenches are along the zigzag direction. The lattice-resolution AFM friction image is Fourier filtered for clarity. b, Occurrences of all trenches obtained via nickel assisted etching versus their azimuthal angle. Histogram shows that three specific angles (-30°, 30° and 90°) are preferred. It indicates that zigzag direction dominates in the trenches etched by Ni nanoparticles. c, AFM friction image of armchair oriented trenches on h-BN cut by platinum particles. The trenches exhibit about -60°, 0° or 60° with respect to the h-BN wrinkles. The green dash line represents a trench orientation while the white dash line denotes a wrinkle orientation. Inset is a zoom-in view of the selected region shown in (c), showing Fourier filtered lattice-resolution AFM friction image, confirming that the trenches are along the armchair direction. d, Occurrences of all trenches obtained via platinum assisted etching versus their azimuthal angle. Histogram shows three specific angles (-60°, 0° and 60°) are preferred by the Pt assisted etching. It means that armchair orientation dominates in all trenches etched by Pt nanoparticles.
Extended Data Fig. 2 | High resolution analysis of ZZ-oriented nano-trenches and ZGNRs embedded in h-BN lattices. a–d, AFM height images of mono-layered ZZ-oriented nano-trenches in h-BN surface by Ni particle-catalyzed cutting. The scale bars are 500, 100, 100 and 200 nm, respectively. The circular inset in (a) shows an atomic-resolution friction image of the h-BN. All the trenches are found along ZZ direction. b, c, show nano-trenches narrower than 5 nm. d, For a ~78 nm-wide trench, the depth profile shows that etching occurs only at the top layer of h-BN substrate. e–h, AFM height images of GNRs embedded in the ZZ-oriented nano-trenches. The width of ZGNRs is less than 10 nm. The scale bars are 500, 200, 100 and 100 nm, respectively. i, A STEM MAADF-α×HAADF image for a ZGNR sample. The scale bar is 200 nm. j, A zoomed-in MAADF image of a region shown in the middle of white dashed frame in (i). The scale bar is 10 nm. k, A Wiener-filtered MAADF image of the region shown in the dashed frame in j. The STEM investigation indicates that the boundaries between GNR and h-BN can be distinguished with a scale bar of 2 nm. The measured in-plane width of the GNR is ~3.2 nm.
Extended Data Fig. 3 | High-resolution characterization of AC-oriented nano-trenches and AGNRs embedded in h-BN trenches. a-d, AFM height images of mono-layered AC-oriented trenches obtained via Pt particle-assisted etching. The scale bars are 500, 100, 100 and 50 nm, respectively. The inset circular in (a) shows atomic-resolution friction image of h-BN. The white hexagons in the inset help with the identification of the atomic structure of GNR. All the trenches are found along AC directions. The width of the trench is less than 5 nm. d, shows an AC-oriented trench in width of ~23 nm, the profile of the depth indicates that etching occurs only at the top layer of h-BN surface. e-h, AFM height images of AGNRs embedded in the AC nano-trenches. The scale bars are 500, 200, 100 and 100 nm, respectively. The width of AGNRs is less than 10 nm. i, STEM-MAADF images of an AGNR sample. j, The magnified image of the AGNR area pointed to by the arrow in i, and the two dashed lines show the boundary between h-BN and AGNR. The scale bar in (i) is 100 nm and in (j) is 3 nm. The width of the GNR is ~5.3 nm. k, The fast Fourier transform (FFT) image for (j), indicating that the GNR is along the AC lattice direction.