Graphene nanoribbons for quantum electronics

Haomin Wang, Hui Shan Wang, Chuanxu Ma, Lingxiu Chen, Chengxin Jiang, Chen Chen, Xiaoming Xie, An-Ping Li and Xinran Wang

Abstract | Graphene nanoribbons (GNRs) are a family of one-dimensional (1D) materials with a graphitic lattice structure. GNRs possess high mobility and current-carrying capability, sizeable bandgap and versatile electronic properties, which make them promising candidates for quantum electronic applications. In the past 5 years, progress has been made towards atomically precise bottom-up synthesis of GNRs and heterojunctions that provide an ideal platform for functional molecular devices, as well as successful production of semiconducting GNR arrays on insulating substrates potentially useful for large-scale digital circuits. With further development, GNRs can be envisioned as a competitive candidate material in future quantum information sciences. In this Perspective, we discuss recent progress in GNR research and identify key challenges and new directions likely to develop in the near future.

Over the past half-century, the feature size of the transistors in integrated circuits has been reduced to nanometres by following Moore’s law, and further device miniaturization faces challenges from both fundamental physics and manufacturing technology, such as short–channel effects and the limits of lithography. To achieve higher performance together with smaller device footprint and reduced power consumption, low-dimensional materials are urgently needed to complement bulk semiconductors. Among them, graphene nanoribbons (GNRs), which can be viewed as quantum confined graphene in one dimension, have attracted enormous interest. GNRs have a number of useful electronic properties, including high mobility and current-carrying capability, sizeable bandgap, long mean free path, localized spin and topological edges states. These properties make them attractive candidates as building blocks for information processing under both classical and quantum schemes.

In realizing topological states and controlling quantum coherence, in particular, GNRs have several potential advantages. First, in GNR structures, two main sources of decoherence, spin–orbit coupling and hyperfine interaction, are both minimal. Second, the bandwidth of the topological electronic band close to the energy scale of proximity-induced spin–orbit coupling can be finely tuned. 

Topological states at GNR junctions and spin-polarized edge states of zigzag-oriented GNRs can both serve as key elements for quantum information devices. Third, the quantum states in GNR nanostructures, once made, can be readily amenable to integration with other materials for assembling into multi-qubit architectures and, ultimately, integrated into systems.

The theoretical investigations on GNRs date back to the 1990s, much earlier than the experimental isolation of monolayer graphene. The theoretical studies investigated the edge and spatial confinement effect using the tight binding calculations. More recently, using advanced first-principles calculations considering the orbital hybridizations and electron–electron interactions, the electronic structures of GNRs have been well understood. Many device concepts from logic transistors to optoelectronics have been theoretically proposed and experimentally realized. In the past 5 years, topological states in GNRs have been engineered using the atomically precise synthesis strategy. As such, it is possible to place unpaired electrons at any location designated within a GNR, so long as it contains an interface between segments with different topologies. This approach can be used to create qubits, quantum spin chains and new 1D band structures.

There are numerous reviews on materials science challenges, bottom-up chemical synthesis, GNR-based electronic devices, theoretical modelling and other aspects of GNRs. This Perspective is not intended to be comprehensive but, instead, we focus on material, device and integration challenges for GNR quantum electronics. We discuss the possible future applications ranging from 3D integration for logic and memory, spintronics to topological quantum information and provide a technological roadmap that summarizes the direction of the field.

Production of graphene nanoribbons

Since 2007, top-down approaches have been adopted for GNR fabrication by lithographic cutting of graphene, sonothermal treatment in solution, unzipping of carbon nanotubes and anisotropic etching technique. These approaches obtained sub-10-nm-wide GNRs with sizeable energy bandgaps, as shown by transport measurements. An important milestone was the demonstration of high on/off ratio GNR-based field-effect transistors (FETs) in both p-doped and n-doped forms, which led to new research interest in studying this type of material.

However, top-down approaches cannot control the width and, especially, the precise atomic structure of GNR edges, and, thus, only chemically less defined GNRs can be obtained, which stymies the accurate control of their properties.

Atomically precise growth. Bottom-up assembly uses small molecular precursors as building blocks to create well-defined GNR structures. The on-surface reaction usually follows a two-stage reaction process, first Ullmann polymerization and then cyclodehydrogenation. In 2010, bottom-up synthesis of armchair GNRs (AGNRs) with width of 7 carbon atoms (7-AGNR) by polymerization of...
Box 1 | Electronic structures of graphene nanoribbons

According to the edge structure, graphene nanoribbons (GNRs) can be mainly classified into three categories: zigzag (ZZ), armchair (AC) and chiral GNRs. ZZ and AC edges go through the [1120] and [10\overline{1}0] directions of the graphene lattice, respectively. Other ordered orientations are chiral, which have a mixture of ZZ and AC edges.

The properties of GNRs depend highly on their edge structures. The nearest-neighbour tight-binding model predicts that all ZZ-edged GNRs (ZGNRs) are metallic\(^8\,^{184}\), the edge states localized at the ZZ edges exhibit ferromagnetic ordering\(^3\,\,^{185}\) and lead to the formation of conducting channels near the Fermi level. Exchange coupling of ferromagnetic states across the ZGNR results in antiferromagnetism and bandgap opening when its width is narrow enough\(^1\,^{12},^{14},^{185}\). The half-metallicity is expected by applying an in-plane transverse electric field to lift the spin degeneracy\(^1\,^{14}\). These magnetic properties render ZGNRs useful in spintronics\(^186,\,^{187}\).

Depending on their widths, AGNRs can be classified into three families: (i) degenerate\(^14\). These magnetic properties render ZGNRs useful in spintronics\(^186,\,^{187}\).

ZGNR results in antiferromagnetism and bandgap opening when its width is narrow enough\(^1\,^{12},^{14},^{185}\). The half-metallicity is expected by applying an in-plane transverse electric field to lift the spin degeneracy\(^1\,^{14}\). These magnetic properties render ZGNRs useful in spintronics\(^186,\,^{187}\). The AGNR superlattice of alternating topologically trivial and non-trivial segments possesses\(^5\,\,^{57}\). Combining scanning tunnelling microscopy and spectroscopy (STM/STS) characterizations with first-principles calculations, a wide range of \(E_g\) (0.1–3 eV) has been demonstrated.

Furthermore, GNR heterojunctions can be rationally designed by welding different precursors\(^3\,\,^{40}\) [FIG. 1c]. Type II band alignment has been demonstrated between the pristine and the N-doped chevron GNRs\(^4\,\,^{59}\) and between the pristine and the fluorenone chevron GNRs\(^4\,\,^{65}\). 7–13 AGNR heterojunctions have been reported with type I band alignment\(^65\). Another approach to form GNR heterojunctions is to fuse the parallel GNRs together, thus, creating 7–14 and 7–14–21 AGNR heterostructures\(^61\). A similar strategy can be applied to GNR and graphene nanodot to form a heterojunction with well-defined quantum well states for narrow-band photoluminescence\(^62\) [FIG. 1d].

Engineering topological states in GNRs enables the formation of topological bands, allowing an increased level of control over the electronic structure of such materials. By mixing precursors and fusing different types of GNR segments\(^5\,\,^{57},^{69}\), topologically protected states were observed at the boundary of the 7-AGNR with staggered edge extensions\(^1\) and at the interfaces between topologically trivial 7-AGNR and non-trivial 9-AGNR segments in the superlattice\(^10\) [FIG. 1e]. This is reminiscent of the Su–Schrieffer–Heeger chain\(^9\), providing a completely new design space to realize exotic topological states for quantum information processing. Very recently, by inserting a symmetrical superlattice of zero-energy modes into otherwise semiconducting GNRs, robust metallic states have been realized in GNRs\(^63\).

So far, most bottom-up assembly processes have been demonstrated on noble metals owing to their catalytic properties. However, the interaction with metallic substrates strongly affects the electronic and optical properties of the GNRs, and the device application would require the transfer of GNRs off the substrate\(^10\). It is, therefore, highly appealing to grow GNRs directly on insulating substrates. Recently, the direct synthesis of 7-AGNR on the surface of rutile TiO\(_2\) has been demonstrated, by combining cyclohydrofluorination and cyclohydrogenation reactions\(^4\) [FIG. 1f].

STS characterizations revealed that the magnetic ground state of the synthesized model open-shell GNRs was electronically decoupled from the substrate. The ability to access the intrinsic properties of GNRs synthesized by the on-surface approach...
not only provides more possibilities for evaluating their potential applications but also offers more convenient platforms for device fabrication.

**Scalability.** For scalable growth, chemical vapour deposition (CVD) can produce GNRs with well-defined edges, chirality and predetermined locations. Recently, SiC [Refs 68–70], hexagonal boron nitride (h-BN) [Refs 68–71] and Ge [Refs 72,73] have been used as template substrates towards this goal. To achieve scalable GNR arrays, sidewalls, trenches or graphene seeds are created by lithography or catalytic etching and then serve as growth templates in the gaseous CVD process (Fig. 2a, b).

On SiC, the orientation of GNRs is determined by the predefined sidewalls. AGNRs and ZGNRs can be obtained on the [1120] and [1100] sidewalls of the mesa structures, respectively, showing distinct properties [73]. ZGNRs resemble ballistic conductors, which exhibit quantum resistance of several $e^2/h$ (where $e$ is the elementary charge and $h$ is the Planck constant) and low on/off ratio [74,75] (Fig. 2c). The result is related to the edge geometry and asymmetrical termination at opposite edges. In contrast, the sidewall AGNRs appear to be strongly corrugated following the topography of the substrate and show higher resistance (Fig. 2d). Surprisingly, even though its width is reduced to just 2–3 nm, the AGNRs on the nano-facets still behave metallic [76–78]. Recently, quasiparticle bandgap formation [79] in very narrow sidewall AGNRs was observed. These conflicting results indicate that the correlation between ribbon geometry and transport behaviour needs further investigation.

$h$-BN is an ideal substrate for GNRs owing to small lattice mismatch ~1.6%, flat surface free of dangling bonds and charge impurities [80]. On $h$-BN, chirality-controlled GNRs can be grown.

---

**Box 2 | A technology roadmap for graphene nanoribbon electronics**

Up to now, graphene nanoribbon (GNR) electronics is still at the stage of laboratory exploration. The main challenges in materials synthesis, device design and circuit integration are listed, and possible solutions are outlined. However, this roadmap is only meant to be a general guideline for GNR research and development because, at this stage, it has many technical and timeline uncertainties. During the course of development, technological evaluation is critical, as GNRs must show performance advantages over other technologies under classical or quantum schemes. Since the electronics technology requires absolute control over the full manufacturing process, transition from fundamental laboratory research to industry development is expected only when most material and device challenges are resolved. At this stage, reliability, process compatibility and scalability will become the main challenges.

**Material**
- Precise edge control: ZZ/AC
- Bandgap: 0.1–3 eV
- Heterostructure and superlattice
- Mostly metallic substrate

**CVD**
- Chirality control: ZZ and AC
- Mobility: ~1,500 cm$^2$/V·s

**High-throughput characterizations**
- STM/STS, STEM, AFM
- Precise but low throughput
- Optical fingerprint of chirality-specific GNRs
- Experiment + calculations

**Logic transistor**
- High on/off ratio: 10$^4$
- ~8 µA per ribbon
- Complementary doping
- Improve device performance
- Mobility: >3,000 cm$^2$/V·s
- Contact resistance: <100 Ω·µm

**Spintronics**
- Spin-polarized edge states
- Coherent time: ~330 ns
- Spin states manipulation
- Robust spin injection, manipulation and readout schemes

**3D heterogeneous integration**
- Manual stacking
- Large-area h-BN dielectric
- Demonstration of GNR-based RRAM/PCRAM
- Development of large-scale integration process

**Quantum computing**
- Creation of topological and spin states
- Narrow-band PL from individual heterojunctions
- Single-photon emitters
- Demonstration of quantum coherence
- Quantum sensing
- Coupled qubits and resonant-exchange multi-qubits

**Material for quantum computing**
- Material for quantum computing
- Tunable spin interactions
- Entanglement of qubits

**Technical system**
- Demonstration of MRAM and spin FET devices
- Development of benchmark evaluation
- Technical benchmark and evaluation

---

**Achieved • Challenge • Possible solution**
using CVD within predefined zigzag or armchair trenches from metal nanoparticle etching[46-48]. Narrow embedded ZGNRs (~7 nm) exhibit $E_g$ greater than 0.4 eV[ref.5]. The gap opening is attributed to a combined influence from $e-e$ interactions, uniaxial strain[58-60], and the stacking order on $h$-BN[ref.64]. Intriguingly, wide ZGNRs always show a pronounced conductance peak in the transfer curves, which is temperature-independent and persists under magnetic fields. The phenomenon is believed to be related to gap states localized at the zigzag edges[84–87]. Narrow embedded AGNRs (~7 nm) exhibit $E_g$ of ~350 meV extracted from device characteristics (Fig. 2f). No obvious conductance peak was observed in AGNRs. It indicates that the opening of $E_g$ is a result of quantum confinement. Importantly, the mobility of the narrow GNRs reaches ~1,500 cm$^2$/V·s, presumably owing to edge passivation and impurity screening by $h$-BN. In addition, multidimensional integration of GNRs with $h$-BN by in-plane covalent bonding[29,58] and van der Waals stacking[79] brings the heterostructure a merit in chemical and mechanical stability, and may lead to emergent properties that are non-existent from the constituents.

The CVD synthesis of GNRs directly on Ge substrate is viable, as single-crystal Ge wafers, which are of proper catalytic activity and low solubility of carbon, are commercially available. Large-area single-crystal graphene is firstly transferred onto the Ge(100) substrate with its 〈110〉 direction aligned with the Ge (110) directions, and then patterned into arrays of graphene nano-seeds. Subsequent CVD growth creates unidirectional arrays of GNRs with high aspect ratio[64,65]. This is because graphene grows anisotropically on Ge(001) owing to heavy interactions between edges of the seed and the surface structure of the underlying substrate.

AGNRs with widths down to 1.7 nm have been achieved on Ge(001) wafer, and their width can be tuned by varying growth time and precursor concentration during CVD[54]. The AGNRs demonstrate a semiconducting band structure and exhibit $I_d/I_{sat} \sim 2 \times 10^4$. Furthermore, the approach can be extended to the complementary metal–oxide–semiconductor (CMOS)–compatible Ge/Si(001) wafer, which is a promising approach towards front-end-of-line integration of GNRs on a Si platform for both logic and analogue/radio frequency applications[55].

Challenges in graphene nanoribbon production. The primary challenge in GNR synthesis is the scalable production of narrow GNRs with atomic precision, on arbitrary substrates and with controllable placement and/or alignment. Up to now, no synthesis method can meet all these criteria. A hybrid approach that combines atomically precise fabrication and scalability of templated growth may bring the field to a new stage.

Edge structure control of general GNRs remains challenging. So far, only GNRs with certain chirality structure have been produced owing to a finite library of precursors. However, the synthesis of GNRs in artificially designed structures is still not possible. In the long term, designing a library of precursors by leveraging artificial intelligence could provide feasible solutions[56].

Reliable formation of devices requires the continuous improvement of GNR length and yield. Limited by surface diffusivity and kinetic factors on substrates, GNRs made from bottom-up assembly have length typically in a range of just tens of nanometres. Engineering the surface of catalytic substrates to enhance surface diffusion or create long smooth steps could benefit the end-fusion of GNRs, therefore, extending their length[57,58]. If the strategy can be extended to crystalline insulators as substrates, the yield and organization of GNR devices could be greatly improved by eliminating the transfer steps.
Approaching these goals needs to develop scalable substrate templates with atomically precise surface. h-BN single crystals could be an ideal potential substrate, and recent progress shows that large-area, high-quality h-BN films can be grown by CVD\(^{99,100}\). When arbitrary GNRs with robust topological states can be created on insulating substrates, we can envision a quantum system with entanglement of qubits and tunable spin exchange interactions by varying their separation distances, which is controlled by the predesigned molecular precursors. Recent work shows that the epitaxial h-BN monolayer can be grown on both Ge(100)\(^{97}\) and Ge(110)\(^{100}\) surfaces with highly aligned orientations in large area by CVD. The GNRs directly deposited on h-BN/Ge could greatly reduce doping from Ge substrate by CVD and void transferring process. Furthermore, the GNRs passivated by h-BN on Ge could effectively improve their chemical/mechanical stability, and, therefore, are worthy of exploration in the future.

Another challenge is characterization. To characterize GNRs in large quantities, development of high-throughput metrology carrying the fingerprint of edge-specific GNRs is needed. To date, STM/STS, scanning transmission electron microscopy and atomic force microscopy are popular tools to characterize the atomic structures of GNRs. These tools are precise but low throughput. For carbon nanotubes (CNTs), the combination of Raman spectroscopy and optical absorption can determine the chirality\(^{99,101}\). A similar database could be established for GNRs, but obviously with much higher complexity due to the open edges. Owing to the limited chirality available, spectroscopies (such as Raman\(^{101,102}\) and photoluminescence\(^{103}\)) need to be performed on these single-chirality GNRs. For AGNRs, the breathing-like modes and shear-like Raman modes are width-dependent, which offers characteristic signatures for quick and effective verifications of the quality and width of GNRs\(^{110,104}\). In addition, a low-energy vibrational mode, namely, the longitudinal compressive mode, displays a well-defined length dependence, which can be used to determine the length information in all families of AGNRs\(^{105}\). Photoluminescence can be an efficient way to probe excitonic behaviours, such as the optical binding.

---

**Fig. 2** | Chemical vapour deposition synthesis and epitaxy on scalable and technologically relevant substrates. **a** | Schematic illustration of the growth process of graphene nanoribbons (GNRs) on silicon carbide (SiC) and hexagonal boron nitride (h-BN) crystals. **b** | Schematic illustration of GNRs growth on germanium (001) substrate\(^{106}\). **c,d** | 3D scanning tunnelling microscopy images of a sidewall zigzag GNR (ZGNR) and armchair GNR (AGNR) on SiC mesa structures oriented along the [1100] and [1120] directions, respectively\(^{73,74}\). The insets show magnification. The lower parts show the characteristic transfer curve of a wide embedded ZGNR or AGNR. The lower inset for sidewall ZGNR shows a measurement result of two-point-probe conductance by moving one of the probes. Transverse movement sequentially reveals the edge channel (red) and body channels (blue and purple) in sidewall ZGNRs\(^91\). **e,f** | Atomic force microscopy height images of embedded ZGNRs and AGNRs, respectively. The insets show atomic-resolution friction images of h-BN. The characteristic transfer curve of a wide embedded ZGNR shows a pronounced conductance peak, which is related to the edge states. The field-effect transistor made of embedded AGNR can be completely switched off, even at room temperature\(^{107}\). **g** | Atomic force microscopy phase image of AGNRs grown on Ge(100) substrate. The characteristic transfer curve of the AGNR grown also shows switch-off features\(^{108}\). Panels **c** and **d** partially adapted with permission from REF\(^{99}\). Panels **e** and **f** partially adapted from REF\(^{101}\). Springer Nature Limited. Panel **g** partially adapted with permission from REF\(^{104}\).
energy\textsuperscript{106–109}, exciton diffusion and recombination, that can potentially give rise to quantum emitters\textsuperscript{62} in GNRs and heterojunctions with uniformed structures. First-principles calculations need to be benchmarked against experimental data, which can then generate a database of optical fingerprints of general GNRs and heterostructures.

### Realizing graphene nanoribbon devices

So far, two types of GNR devices have been explored for electronics. The semiconducting GNRs hold great potential for scaled logic transistors, while the exotic magnetic and spin-polarized edge states open up exciting possibilities for spintronics.

#### Logic transistor

A major bottleneck for GNR transistors is to achieve competitive performance over CNTs and 2D materials, which share the advantage of low dimensionality. For example, a single CNT ballistic transistor can deliver current approaching 25 μA (REF\textsuperscript{109}) and monolayer MoS\textsubscript{2} can deliver a current density of 1,135 μA μm\textsuperscript{−1} (REF\textsuperscript{110}). So far, a saturation current of only ~8 μA was realized in narrow AGNRs\textsuperscript{8}. Scattering from edge defects substantially degrades the mobility and saturation velocity in narrow GNRs compared with graphene. This leads to a trade-off between mobility and \( I_s \). Keeping GNR edges in atomic smoothness and passivating them in \( h \)-BN lattice can greatly suppress the scattering \textsuperscript{129}. In addition, encapsulation by \( h \)-BN can preserve the mean free path and mobility due to the atomically flat, and charge-impurity-free, surface of \( h \)-BN with high optical phonon energy\textsuperscript{130}.

Contact resistance (\( R_c \)) dominates the total resistance in ultra-scaled transistors. A large Schottky barrier from work function mismatch, Fermi level pinning due to gap states and interface contaminations from device fabrication may all contribute to the increase of \( R_c \). Unfortunately, few experimental works are dedicated to this topic. Here, we borrow the wisdom from the CNT and 2D materials community and propose some approaches to minimize \( R_c \). For example, graphene can be used as interlayer, which can prevent the Fermi level pinning effect\textsuperscript{112}. Ultra-close electrodes of graphene fabricated using current breakdown\textsuperscript{113,114} or etching\textsuperscript{115} could form connections to relatively short GNR segments. The recent successful wafer-scale growth of graphene\textsuperscript{116–122} could enable the mass production of GNR devices with this type of contact. Searching for metals with suitable work function to reduce Schottky barrier, formation of covalent bonding of GNR/metal and creating end-bond structure are alternative technologies that can improve the contact\textsuperscript{112}. As a guideline, modern silicon transistors have \( R_c \) less than 100 Ω·μm, and the lowest \( R_c \) for 2D semiconductor devices is 123 Ω·μm (REF\textsuperscript{115}).

Theoretically, a single GNR can deliver maximum on-state current (\( I_{\text{on}} \)) of more than ~1.5 mA μm\textsuperscript{−1} (REF\textsuperscript{123}). Alignment of GNR arrays in a density of 100–200 GNRs per micrometre (corresponding to 5–10 nm pitch) is highly desired for the fabrication of channels in integrated circuits\textsuperscript{124,125}. An array not only increases the number of conducting pathways for a given channel width but also limits screening among them. These requirements on precise control over width and arrangement of GNRs are very stringent. In addition, stacking layers of GNR devices vertically with the help of an insulator, like \( h \)-BN, may increase integration density and, therefore, increase drive current per footprint with relatively long channel lengths.

To assess the potential and facilitate advancement of GNR electronics, it is critical to benchmark their device performance with other emerging materials. In Table 1, we summarize the state-of-the-art performance metrics achieved in GNR devices and compare with CNTs, MoS\textsubscript{2} and silicon. GNRs, CNTs and MoS\textsubscript{2} all feature dangling-bond-free surface, atomically thin nature, appropriate bandgap and theoretically higher mobility compared with their silicon counterpart. These features could enable extremely scaled, below-5-nm-node devices for high-performance and low-power computing. At present, \( I_{\text{on}} \) values achieved in single GNR devices remain inferior to other emerging devices. Achieving comparable \( I_{\text{on}} \) values in GNR-based devices requires the use of dense array (100–200 GNRs per micrometre, equivalent to 5–10 nm pitch) as well as 3D stacking (similar to Si nanosheets). So far, dense GNR arrays with 50 nm pitch have been realized\textsuperscript{127}. Reducing the pitch to 10 nm with large-area uniformity remains a technologically challenging task. Combining dense arrays with 1 nm equivalent oxide thickness high-\( k \) gate, GNR transistors with high \( I_{\text{on}} \) above 1,000 μA μm\textsuperscript{−1} and high on/off ratio of 10\textsuperscript{5} can be expected. These values are comparable to 5 nm node Si FinFET technology in the 2020 International Roadmap for Devices and Systems (IRDS)\textsuperscript{128}. Compared with devices based on CNTs, MoS\textsubscript{2} and Si, the subthreshold swing (SS) of GNR transistors is relatively large, which may originate from interface states due to dangling edges, as well as relatively large equivalent oxide thickness. Lower SS is expected by optimizing the device structure (such as side-gated transistor\textsuperscript{129}) or proper edge passivation. There is still much room for dielectric/gate engineering to improve electrostatic control over the GNR channel. Overcoming the above technical challenges in developing channels, contacts, dielectrics, thermal interface and device geometry will further push the performance limit of GNR transistors.

#### Spintronic device

GNRs open up new possibilities for technological co-implementation of spin generation and...
manipulation on a common circuit platform. From a practical point of view, the spin stiffness predicted for the magnetic edges in GNRs is higher than traditional magnetic materials\(^{129}\), and, thus, ZGNRs would possess higher Curie temperatures than room temperature\(^{130}\). The spin coherence time in decorated ZGNRs reaches \(~330\,\text{ns}\) even at room temperature\(^{131}\). In addition, GNRs possess long spin correlation length, low density of state and small feature size. All of the attractive properties are promising for the GNRs to construct building blocks for spintronic circuitry.

Several prototypes of device configurations for controlling the spin transport have been proposed, which use spin-polarized GNRs as building blocks (Fig. 3a). One of them is magnetic tunnel junction, which is a highly desirable component for magnetoresistive random-access memory. A typical magnetic tunnel junction is composed of two ZGNRs separated by a thin dielectric layer. One ZGNR selectively filters the spin direction by a transverse electric field\(^{132}\), while the other ZGNR with defects on one edge generates a pure spin current by quenching magnetic moments and scattering the carriers at the rough edge\(^{133,134}\). Any change in the spin polarization in the two GNRs could result in the variation of tunnelling conductance. A spin-based FET could be another promising prototype to enable an electrical manipulation of spin currents, inspired by the proposal of spin modulator\(^{132}\) (Fig. 3b). The spin–orbit field serves as a means for electrical control of the spin current\(^{132,134}\).

In either device concept, a short-term target is the ability to inject spins in GNRs and detect their transport. Ferromagnetic resonance of spin pumping\(^{135}\) is expected to inject spin into the GNR without any tunnel barriers. The detection of spin currents could be realized even without the use of magnetic contacts\(^{136}\). The realization of spin degree of freedom through the field effect in GNRs could potentially be used for Boolean logic computing, as well as unconventional computing schemes such as neuromorphic and probabilistic computing.

**Towards integration and applications**

**3D heterogeneous integration**. To realize GNR-based device technology, integration of various components into a circuitry is an essential step. Electrostatic control lies at the heart of modern integrated circuits. Introducing the structures of gate-all-around FETs can realize better electrostatic control in GNR-based circuits (Fig. 3c). In the 3-nm technology node, Si CMOS technology will switch to stacked nanosheet geometry to suppress leakage. To this end, GNR as a natural nanosheet offers the advantage of an ultra-thin body compared with bulk semiconductors. Stacking layers of GNRs vertically in 3D will further increase the device density and promise a high \(I_{\text{on}}\) comparable to ultra-scaled CMOS.

Owing to their ballistic conductivity, GNRs can also serve as contact electrodes for cells in phase-change random-access memory\(^{137}\) or resistive random-access memory\(^{138}\) (Fig. 3d). One-transistor-one-resistor memory cells may be realized by co-integration of GNR-based transistors and non-volatile memories\(^{137}\). A narrow GNR not only reduces the active volume of phase-change material in each cell but also serves as a channel of FET with high on/off ratio. The one-transistor-one-resistor architecture features excellent scalability and benefits in-memory computing by reducing the amount of data transfer by performing computations inside the memory arrays.

Data-centric applications in machine learning and scientific computing benefit the most from reduced memory access. In future monolithic 3D architectures, GNRs could enable efficient heat dissipation owing to their high thermal conductivity of \(~5,000\,\text{W/m}\cdot\text{K}\) (Ref.\(^{139}\)). It points to a potential use as heat spreader on-chip. Meanwhile, the atomically thin nature of GNRs enables smaller tier thickness and \(~150\%\) higher packing efficiency than...
that in traditional integrated circuits\textsuperscript{146}. With the decrease of wire pitches, Cu interconnects suffer from a lot of scattering at their surfaces and grain boundaries, which leads to increased self-heating and stability issues\textsuperscript{147}. A GNR barrier can keep Cu interconnect resistivity near its intrinsic value, regardless of wire width scaling\textsuperscript{148}. GNRs themselves exhibit a breakdown current density of \textasciitilde10 \textsuperscript{A cm\textsuperscript{-2}} (REF.\textsuperscript{149}), which is two orders higher than Cu wires\textsuperscript{150}. Engineering multilayer GNRs through intercalation doping further increases current-carrying capability\textsuperscript{151}. Therefore, GNRs are potentially useful as interconnects in advanced technology nodes.

The IRDS predicts that the dimensional scaling of CMOS technology is reaching fundamental limits. Development of large-scale integration processes would be fuelled by heterogeneous integration of GNRs on a silicon platform. From an industrial point of view, research knowledge from technical benchmarking and mature evaluation should be used to develop electronic design automation tools in early pilot lines to access the basis in module integration.

**Quantum computing**. High-quality single-photon emitters (SPEs) and entangled spin centres are at the core of quantum information and quantum computing (FIG. 3e,f). SPEs emit one photon at a time with a well-defined frequency and polarization in a deterministic fashion. SPEs play an important role in many leading quantum information science (QIS) technologies, with applications in quantum sensing\textsuperscript{152}, quantum communications\textsuperscript{153} and quantum simulation\textsuperscript{154}. However, there is still no ‘ideal’ on-demand, high-purity, indistinguishable SPE. Tuning the electronic structures of GNRs by defect engineering provides a unique opportunity for creating SPEs deterministically. Owing to the long coherence length and precision structural control in the GNRs, photo-generated excitons can transfer ballistically to localized defect centres to emit high-purity photons, in GNR–graphene nanotand heterojunctions\textsuperscript{155}. Obviously, photon statistics analysis needs to be carried out to characterize the single-photon purity, generation efficiency and indistinguishability. These ‘defect-engineered’ states in GNRs enable the creation of a new family of quantum materials, providing an essential avenue for quantum optoelectronics.

Topologically protected electronic states provide a natural route to phase coherence and entanglement, which are important for quantum information processing and high-efficiency quantum computation\textsuperscript{156,157}. However, even for GNRs with predefined topological states, it is still non-trivial to realize quantum information processing. For example, understanding how to build qubits with long relaxation and coherence times is critical. The spin coherence time in ZGNRs decorated with radical molecules that bear electron spins can last microseconds, even at room temperature\textsuperscript{158}. When the GNRs are coupled to a solid-state device, spin–phonon interaction and environmental noise are two common sources of decoherence. The former is caused by absorption or emission of one phonon in resonance of two electron spin states, while the latter includes random flips of spin and charge instability, which have been extensively explored in shallow spins of diamond\textsuperscript{159–161}. Strain tuning\textsuperscript{162} to engineer the phononic bandgap could suppress decoherence by weakening the spin–phonon resonant processes. Placing GNRs on a substrate with different wavelengths of relevant acoustic phonons and a clean electromagnetic environment may preserve coherence time for spins.

Another challenge in the development of the GNR-based quantum devices is information manipulation and readout. Semiconducting AGNRs with lifted valley degeneracy allow Heisenberg exchange coupling for spins in these electrostatically defined neighbouring qubits\textsuperscript{163}. The spin qubits can be easily manipulated by an external electric field or coupled remotely with microwave resonators, whereas the valley qubits can be controlled with an a.c. electric field without affecting the spin. In addition, simultaneous flipping of the spin and valley states can be achieved in spin–valley qubits using near-range defects, a.c. electric fields and off-axis magnetic fields. Further understanding of interactions between the quantum states and identification of the environmental and external variables that can suppress decoherence or be utilized to control the quantum behaviours are urgently needed for GNR-based quantum applications.

Implementation of quantum computing necessitates manufacturing capabilities that allow fabrication of arrays of well-characterized qubits in a scalable fashion, the ability to initialize a set of qubits to a known quantum state and the ability to measure/read the state of the qubit at arbitrary time\textsuperscript{164}. Local gating\textsuperscript{165} is a convenient strategy for reading, manipulating and initializing the qubits in these GNRs. Moreover, GNRs with coupled qubits or resonant-exchange multi-qubits\textsuperscript{166,167} serve as building blocks, and the ability to arrange them in different ways provides significant versatility in qubit integration, which facilitates scalable processing into more complex qubit systems\textsuperscript{168}. To couple the remote multi-qubits, superconducting microwave resonators offer a means to entangle macroscopically separated quantum systems on a chip. The available qubits and their manipulations determine the quantum algorithm, where the operators perform specific functions on one qubit or more\textsuperscript{169,170}. In addition, quantum sensing via qubits or entangled photons has become a distinct and rapidly growing frontier of QIS. GNRs are expected to provide new opportunities for many areas in applied physics and QIS.

**Outlook**

GNRs are promising materials for semiconductor technologies and QIS. Although challenges remain in synthesis, devices and integration, GNRs provide many opportunities in future classical and quantum electronics.

In particular, we believe that bottom-up synthesis and epitaxy on templated crystalline substrate offer promising solutions to meet materials requirements. Optimization of GNRs enables different transistor building blocks: semiconducting GNRs for the channel and quasi-metallic ones for interconnects. One approach is to make seamless contacts in GNRs through the formation of an atomic staircase heterostructure\textsuperscript{171}, where the wide GNRs, either quasi-metallic or in small-gap, can serve as an optimal electrical contact to the wide-gap 1D semiconducting segments. For functional nanodevices, GNR heterojunctions with controlled sequence and position of interfaces along the length of a ribbon are highly desired, especially for the topologically protected junction states\textsuperscript{172}. By adopting a hierarchical fabrication strategy, bottom-up GNRs with preferential single heterojunctions have been achieved\textsuperscript{163}. Meanwhile, methods to fabricate arrays of single-chirality GNRs in well-controlled density and alignment are needed\textsuperscript{165,164}, which will further advance transistor performance. Monolithic 3D integration and hetero-integration will harness the promises of GNRs to deliver packing density and energy efficiency beyond bulk semiconductors.

In addition, novel device concepts need to be further explored, including spintronic and topological devices potentially useful in quantum computing. It is now generally
recognized that entanglement and coherence provide the fundamental resource for a new QIS revolution with widespread practical applications in quantum computing, networking and sensing\(^{49,130}\). By precisely positioning defects or junctions to trap electronic states, single and entangled photon emitters can be created, while controlled local geometry in a superlattice can lead to topologically protected spin centres. It is, thus, possible to create qubits, quantum spin chains and new 1D band structures in GNR superlattices. This strategy makes GNRs a promising materials system for topological nanodevices and quantum computers with significantly enhanced coherence and entanglement.

Specific efforts of modelling are needed during each stage of development, for instance, on appropriate doping, defect and edge modification, contact designs and environmental coupling, such as electron–electron, electron–phonon and out-of-equilibrium effects at larger bias. High-accuracy quantum transport code\(^{165}\), which uses density functional theory and self-consistent non-equilibrium Green's function theory, has been developed. Recently, it has been significantly enhanced and adapted to high-performance computer architectures, and is now able to handle more than 10,000 atoms in the 'active device' part of the simulations, which means that multiple electrodes can be included in the full quantum transport simulation\(^{166}\). Using the self-consistent non-equilibrium Green's function method, calculations of the negative differential resistance in the traditional double-barrier resonant-tunnelling diode model based on GNR heterojunctions have uncovered important issues at the atomic scale; these issues can be solved by using experimentally fabricated multicomponent GNR heterostructures\(^{167}\). First-principles quantum transport simulations on T-shaped and crossed junctions of GNRs suggest those all-carbon-based junctions to be a promising candidate for nanoelectronic devices\(^{168}\). Four-terminal electronic devices composed of two crossed GNRs were proposed to realize electronic beam splitters\(^{169,270}\), showing importance in the context of twistronics. These state-of-the-art calculation methods can guide the design of novel GNR-based quantum nanoelectronic devices.

Just as achieving control over the physical and electronic properties of semiconductors was instrumental in the rise of the information age, the key to success in the development and application of QIS is to realize materials where rationally designed structures define electrons, spins and photons into coherent and entangled states to carry energy and information in unique ways. This will allow efficient transport of energy, quantum information processing and computing, ultra-sensitive sensors and low-power electronics. The synergistic efforts by a cross-disciplinary community of synthetic chemists, physicists, materials scientists and electrical engineers are critical for pushing GNR research to a new level of mainstream industry technology.

Nature Reviews Physics.

**Perspectives**

*Hefei National Laboratory for Physical Sciences at the Microscale and Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui, P. R. China.*

*School of Materials Science and Physics, China University of Mining and Technology, Xuzhou, Jiangsu, P. R. China.*

*School of Physical Science and Technology, ShanghaiTech University, Shanghai, P. R. China.*

*Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN, USA.*

*National Laboratory of Solid State Microstructures, School of Electronic Science and Engineering and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing, Jiangsu, P. R. China.*

*These authors contributed equally: Haomin Wang, Hui Shan Wang, Chuanxu Ma.*

*e-mail: hmwang@mail.sim.ac.cn; xmnie@ mail.sim.ac.cn; apli@onlrf.gov; xxwang@nju.edu.cn*

Published online 28 September 2021

1. Mack, C. A. Fifty years of Moore’s law. IEEE Trans. Semicond. Manuf. 26, 202–207 (2013).

2. Thompson, S. E. et al. In search of “Forever,” continued transistor scaling one new material at a time. IEEE Trans. Semicond. Manuf. 18, 26–36 (2005).

3. Ito, T. & Okazaki, S. Pushing the limits of lithography. Nature 406, 1027–1031 (2000).

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. Son, Y. W., Cohen, M. L. & Louie, S. G. Energy gaps in graphene nanoribbons. Phys. Rev. Lett. 97, 216805 (2006).

6. Baringhaus, J. et al. Exceptional ballistic transport in epitaxial graphene nanoribbons. Nature 506, 349–354 (2014).

7. Report of ballistic transport behaviour of charge carriers in GNRs that makes them of great interest for high-speed electronic applications.

8. Magda, G. Z. et al. Room-temperature magnetic order on zigzag edges of narrow graphene nanoribbons. Nature 514, 608–611 (2014).

9. First experimental report of ZGNRs exhibiting clear magnetic ordering at room temperature that makes them prospects for spintronic devices.

10. Cao, T., Zhao, F. & Louie, S. G. Topological phases in graphene nanoribbons: junction states, spin centers, and quantum spin chains. Phys. Rev. Lett. 119, 076401 (2017).

11. Groening, O. et al. Engineering of robust topological quantum phases in graphene nanoribbons. Nature 560, 209–213 (2018).

12. Rizzo, D. J. et al. Topological band engineering of graphene nanoribbons. Nature 560, 204–208 (2018).

13. Slota, M. et al. Magnetic edge states and coherent manipulation of graphene nanoribbons. Nature 557, 661–695 (2018).

14. Fujita, M., Wakabayashi, K., Nakada, K. & Kasahara, K. Peculiar localized state at zigzag graphite edge. J. Phys. Soc. Jpn. 65, 1920–1923 (1996).

15. Novoselov, K. S. et al. Electric field effect in atomically thin carbon films. Science 306, 666–669 (2004).

16. Sun, Y.-W., Cohen, M. L. & Louie, S. G. Half-metallic graphene nanoribbons. Nature 444, 547–549 (2006).

17. 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).

18. Duy Khanh, N., Ngoc Thanh Thuy, T., Thanh Tien, N. & Lin, M.-F. Diverse electronic and magnetic properties of chlorination-related graphene nanoribbons. Sci. Rep. 8, 17859 (2018).

19. Zhang, Q., Fang, T., Xing, H., Seabaugh, A. & Jena, D. Graphene nanoribbon tunnel transistors. IEEE Electron Device Lett. 29, 1544–1546 (2008).
18. Zhao, P., Chauhan, J. & Guo, J. Computational study of tunneling transistor based on graphene nanoribbon. Nano Lett. 9, 684–688 (2009).
19. Lee, E. J. H., Balasubramanian, K., Weitz, R. T., Burgard, M. & MacLachlan, M. J. Contact and edge effects in graphene devices. Nat. Nanotechnol. 3, 486–490 (2008).
20. Li, Y., Wang, X., Zhang, L., Lee, S. & Dai, H. Chemically derived, ultrasmooth graphene nanoribbon semiconductors. Science 319, 1229–1232 (2008).
21. Dementyev, V. D. Non-classical non-wire-like GNRs using chemical sonication and field-effect transistors with high on/off ratio of 10^4 at room temperature. J. Phys. D: Appl. Phys. 40, 232203 (2007).
22. Wang, X. et al. Room-temperature all-semiconducting sub-10-nm graphene nanoribbon field-effect transistors. Phys. Rev. Lett. 100, 206803 (2008).
23. Systematic investigation of sub-10-nm wide nanoribbon using GNR field-effect transistor performance.
24. Xia, F., Mueller, T., Lin, Y.-M., Valdes-Carica, A. & Avouris, P. Ultrastable graphene photodetector. Nat. Nanotechnol. 4, 839–843 (2009).
25. Wang, X. et al. N-doping of graphene through electrothermal reactions with ammonia. Science 324, 768–771 (2009).
26. Saravas, W., Jaccobberger, R. M. & Arnold, M. S. Graphene nanoribbons: fabrication, properties and devices. J. Phys. D: Appl. Phys. 49, 143001 (2016).
27. Marmozej-Tojada, J. M. & Velasco-Medina, J. Review on graphene nanoribbon devices for logic applications. Microelectron. J. 48, 18–38 (2016).
28. Celis, A. et al. Graphene nanoribbons: fabrication, properties and devices. J. Phys. D: Appl. Phys. 49, 143001 (2016).
29. Shende, P., Augustine, S. & Prabhakar, B. A review on graphene nanoribbons for advanced biomedical applications. Carbon Lett. 30, 465–470 (2020).
30. Chen, Z., Lin, Y.-M., Rooks, M. J. & Avouris, P. Graphene nanoribbon electronics. Phys. E Low Dimens. Syst. Nanosta. 40, 228–232 (2007).
31. Experimental work reporting the field-effect properties of GNRs produced by nanofabrication techniques.
32. Han, M. M., Ozylmac, B., Zhang, Y. & Kim, P. Energy band-gap engineering of graphene nanoribbons. Appl. Phys. Lett. 100, 252105 (2017).
33. Jiao, L., Zhang, L., Wang, X., Dankov, G. & Dai, H. Narrow graphene nanoribbons from carbon nanotubes. Nano Lett. 32, 2009–2013 (2020).
34. Kosynkin, D. V. et al. Longitudinal unzipping of carbon nanotubes to form graphene nanoribbons. Nature 462, 1111–1114 (2009).
35. Jiao, L., Wang, X., Dankov, G., Wang, H. & Dai, H. Facile synthesis of high-quality graphene nanoribbons. Nat. Nanotechnol. 5, 521–525 (2010).
36. Wang, R. et al. An exotic etching effect in the graphene basal plane. Adv. Mater. 22, 4014–4019 (2010).
37. Wang, X. & Dai, H. Etching and narrowing of graphene from the edges. Nat. Chem. 2, 661–665 (2010).
38. Li, X. et al. Simultaneous nitrogen doping and redox reaction of graphene. J. Am. Chem. Soc. 131, 15395–15399 (2009).
39. Tapasito, L., Dobrik, G., Lambin, P. & Biro, L. P. Tailoring the atomic structure of graphene nanoribbons by scanning tunneling microscope lithography. Nat. Nanotechnol. 3, 597–401 (2008).
40. Schmidt, M. et al. Dielectric-screening reduction-induced large transport gap in suspended sub-10 nm graphene nanoribbon functional devices. Small 15, 1903053 (2019).
41. Hasan, M. S. & Lu, X. Promising lithography techniques for next-generation logic devices. Nanonanof Metrol. 1, 67–81 (2018).
42. Tahir, A., Buhlmann, B., Schuler, R. & Bihlmayer, K. On-surface synthesis of atomically precise graphene nanoribbons. Adv. Mater. 28, 6222–6231 (2016).
43. Chao, Z. et al. Realization of chirality control of graphene nanoribbons embedded in hexagonal boron nitride. Nano Lett. 17, 2681–2689 (2017).
44. Shah, P., Chaaban, J. & Guo, J. Computational study of tunneling transistor based on graphene nanoribbon. Nano Lett. 9, 684–688 (2009).
45. Zhao, P., Chauhan, J. & Guo, J. Computational study of tunneling transistor based on graphene nanoribbon. Nano Lett. 9, 684–688 (2009).
46. Tahir, A., Buhlmann, B., Schuler, R. & Bihlmayer, K. On-surface synthesis of atomically precise graphene nanoribbons. Adv. Mater. 28, 6222–6231 (2016).
47. Chao, Z. et al. Realization of chirality control of graphene nanoribbons embedded in hexagonal boron nitride. Nano Lett. 17, 2681–2689 (2017).
48. Zhang, H. et al. On-surface synthesis of n-type graphene nanoribbons. J. Am. Chem. Soc. 137, 4022–4025 (2015).
49. Tahir, A., Buhlmann, B., Schuler, R. & Bihlmayer, K. On-surface synthesis of atomically precise graphene nanoribbons. Adv. Mater. 28, 6222–6231 (2016).
50. Balasubramanian, K., Weitz, R. T., Burgard, M. & MacLachlan, M. J. Contact and edge effects in graphene devices. Nat. Nanotechnol. 3, 486–490 (2008).
51. Schmidt, M. E. et al. Dielectric-screening reduction-induced large transport gap in suspended sub-10 nm graphene nanoribbon functional devices. Small 15, 1903053 (2019).
52. Hasana, M. S. & Luo, X. Promising lithography techniques for next-generation logic devices. Nanonanof Metrol. 1, 67–81 (2018).
53. Tahir, A., Buhlmann, B., Schuler, R. & Bihlmayer, K. On-surface synthesis of atomically precise graphene nanoribbons. Adv. Mater. 28, 6222–6231 (2016).
54. Chao, Z. et al. Realization of chirality control of graphene nanoribbons embedded in hexagonal boron nitride. Nano Lett. 17, 2681–2689 (2017).
Yuan, G. et al. Proton-assisted growth of ultra-flat nanoribbons. Phys. Status Solidi D 256, 1900343 (2019).

Barin, G. B. et al. Surface-synthesized graphene nanoribbons for room temperature switching devices: Substrate transition and its situ characterization. ACS Appl. Nano Mater. 2, 2188–2192 (2019).

Overbeck, J. et al. Universal length-dependent vibrational mode in graphene nanoribbons. ACS Nano 13, 10385–10391 (2019).

Senkovskiy, B. V. et al. Making graphene nanoribbons photoluminescent. Nano Lett. 17, 4029–4037 (2017).

Pfeiffer, M. et al. Observation of room-temperature photoluminescence blinking in armchair-edge graphene nanoribbons. Nano Lett. 18, 7038–7044 (2018).

Alavi, S. K. et al. Photoluminescence brightening in graphene nanoribbons. 2D Mater. 6, 055009 (2019).

Janotti, A. & Lockhart, T. A. Non-ballistic transport in short carbon nanotubes. Phys. Rev. Lett. 92, 106804 (2004).

Shikinov, P. C. et al. Ultralow contact resistance between semimetal and monolayer semiconductors. Nature 593, 211–217 (2021).

Alexander, J. P. et al. Encapsulation of graphene transistors and vertical device integration by interface engineering with atomic layer deposited oxide. 2D Mater. 4, 011008 (2016).

Park, Y. et al. Extremely low contact resistance on graphene through n-type doping and edge contact design. Adv. Mat. 28, 866–870 (2016).

El Abbassi, M. et al. Convallinolium dinitrogen quantum dot formation in atomically engineered graphene nanoribbon field-effect transistors. ACS Nano 14, 5754–5762 (2020).

Sun, Q. et al. Massive Dirac fermion behavior in a low bandgap graphene nanoribbon near a topological phase transition. Phys. Rev. Applied 12, 196054 (2020).

Braun, O. et al. Optimized graphene electrodes for contacting graphene nanoribbons. Carbon 184, 338–346 (2021).

Li, X. S. et al. Large area synthesis of high-quality and large-area graphene nanoribbons. Nat. Nanotechnol. 5, 374–382 (2010).

Rakheja, S., Kumar, V. & Naeemi, A. Evaluation of the potential performance of graphene nanoribbons as on-chip interconnects. Proc. IEEE 101, 1740–1765 (2013).

Ferrand, J. et al. Realization of room-temperature phonon-limited carrier transport in monolayer MoS2 by dielectric and carrier screening. Adv. Mater. 28, 552–565 (2016).

Carbon nanotube. Wikipedia https://en.wikipedia.org/wiki/Carbon_nanotube.

Mertens, H. et al. Gate-all-around transistors based on quantum-well states in graphene nanoribbons heterojunctions. Phys. Rev. Appl. 12, 044018 (2019).

Smets, Q. et al. in IRDS™ 2020 Edition. IEEE https://irids.ieee.org/editions/2020 (2020).
186. Awschalom, D. D. & Flatté, M. E. Challenges for semiconductor spintronics. Nat. Phys. 3, 153–159 (2007).
187. Chappert, C., Fert, A. & Van Dau, F. N. The emergence of spin electronics in data storage. Nat. Mater. 6, 813–825 (2007).
188. Barone, V., Hod, O. & Scuseria, G. E. Electronic structure and stability of semiconducting graphene nanoribbons. Nano Lett. 6, 2748–2754 (2006).
189. Brey, L. & Fertig, H. A. Electronic states of graphene nanoribbons studied with the Dirac equation. Phys. Rev. B 73, 235411 (2006).
190. Wang, J., Zhao, R., Yang, M., Liu, Z. & Liu, Z. Inverse relationship between carrier mobility and bandgap in graphene. J. Chem. Phys. 138, 084701 (2013).
191. Jacobberger, R. M. & Arnold, M. S. High-performance charge transport in semiconducting armchair graphene nanoribbons grown directly on germanium. ACS Nano 11, 8824–8829 (2017).
192. Ohtomo, M., Sekine, Y., Hibino, H. & Yamamoto, H. Graphene nanoribbon field-effect transistors fabricated by etchant-free transfer from Au(111). Appl. Phys. Lett. 112, 021602 (2018).
193. Trauzettel, B., Bulaev, D. V., Loss, D. & Burkard, G. Spin qubits in graphene quantum dots. Nat. Phys. 3, 192–196 (2007).
194. Droth, M. & Burkard, G. Electron spin relaxation in graphene nanoribbon quantum dots. Phys. Rev. B 87, 205432 (2013).
195. Carvalho, A. R., Wannas, J. H. & Lewenkopf, C. H. Edge magnetization and local density of states in chiral graphene nanoribbons. Phys. Rev. B 89, 245444 (2014).
196. Lopez-Sanchez, M. P. & Brey, L. Charged topological solitons in zigzag graphene nanoribbons. 2D Mater. 5, 015026 (2018).
197. Lee, Y.-L., Zhao, F., Cao, T., Ihm, J. & Louie, S. G. Topological phases in cove-edged and chevron graphene nanoribbons: Geometric structures, z invariants, and junction states. Nano Lett. 18, 7247–7253 (2018).

Acknowledgments
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. XDB50000000), National Natural Science Foundation of China (Grant Nos. 61734005, 61521001, 61927808, 61851401, 91964202, 6186116601, 51861145202, 51772517, 91964102, 12004406, 22002149), the Science and Technology Commission of Shanghai Municipality (Grant No. 20D22205600), Leading-edge Technology Program of Jiangsu Natural Science Foundation (Grant No. BK2020005), China Postdoctoral Science Foundation (Grant No. BX2021331), Collaborative Innovation Center of Solid-State Lighting and Energy-Saving Electronics, the Fundamental Research Funds for the Central Universities, China, and Soft Matter Nanofab (SMN180827) of ShanghaiTech University. C.M. acknowledges support from the Chinese Academy of Sciences (CAS). A portion of the work (A.-P.L) was conducted at the Center for Nanophase Materials Sciences (CNMS), which is a DOE Office of Science User Facility, and supported by grant ONR N00014-20-1-2502.

Author contributions
X.W. conceived the Perspective article. H.W., A.-P.L., X.X. and X.W. drafted the manuscript, with contributions from H.S.W., C.M., L.C., C.J. and C.C. All authors have read, discussed and contributed to the writing of the manuscript.

Competing interests
The authors declare no competing interests.

Peer review information
Nature Reviews Physics thanks Byung Hee Hong and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Publisher’s note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© Springer Nature Limited 2021