Two-dimensional materials of group-IVA boosting the development of energy storage and conversion

Qiang Guo¹ | Nan Chen¹ | Liangti Qu¹,²,³

¹Key Laboratory of Photoelectronic/Electrophotonic Conversion Materials, Key Laboratory of Cluster Science, Ministry of Education of China, School of Chemistry and Chemical Engineering, Beijing Institute of Technology, Beijing, China
²Key Laboratory for Advanced Materials Processing Technology, Ministry of Education of China, State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing, China
³Department of Chemistry, Tsinghua University, Beijing, China

Abstract
Graphene, an emerging fabric of carbon atoms, has manifested its versatility in all kinds of fields encompassing electronics, optoelectronics, thermoelectrics, taking advantage of its excellent mechanical strength, exceptional electronic and thermal conductivities, high surface specific area, and so forth. The prosperity of graphene never seen before has led the attention to silicene, siloxene, germanene, stanene, and plumbene due to their promising applications in the quantum spin Hall effect, topological insulator, batteries, capacitors, catalysis, and topological superconductivity. Herein, we review the existing production methods, numerous applications of two-dimensional group-IVA materials, and critically discuss the challenges of these materials, providing potential implications to the exploration of uncharted material systems.

KEYWORDS
germanene, graphene, plumbene, silicene, siloxene, stanene

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1 | INTRODUCTION

Dimensionality is a vital parameter that profoundly depends on the reactivity of materials under same reaction condition. The thickness of layered materials is decreased to single-atom nanosheets, which will make materials exhibit unique and fascinating physical properties. As it is known to all, two-dimensionality is conspicuously beneficial for fast ion and electron transport. Owing to the extreme absence of experimentally known two-dimensional (2D) materials, it is urged to mechanically and chemically exfoliate stacked 2D layered materials, such as graphite, metal dichalcogenides, boron, black phosphorus, metallic antimony with strong in-plane chemical bonds and weak Van der Waals (vdWs) bonds between layers, to be freestanding monolayer or few layers. Nanosheets obtained through various synthetic methods determine their electrical, thermal, and mechanical properties. To achieve the best performance of devices based on them, employing a suitable synthetic method for controllable and scalable production of high-quality nanosheets is greatly necessary and important. As a widespread and nontoxic element on the earth, 2D carbon-based materials are always hotspots in scientific research. Among the 2D materials of group-IVA, graphene, a superior electronic and thermal conductor, is the first and the most extensively explored one and possesses a variety of intriguing features, such as easy synthesis, high specific surface area, tunable electronic structure, and the feasibility of structural modification and functionalization. These contribute to its versatile utility in many fields. As graphene, a single-atom-thick nanosheet with sp²-hybridized carbon atoms, was mechanically exfoliated from graphite,¹ many efforts have been taken to enrich its fascinating properties and expand its a large range of applications, including batteries,²-⁵ supercapacitors,⁶-⁸ catalysis,⁹-¹⁷ solar water evaporation,¹⁸-²² moist electric generator,²³-²⁶ similar to graphene, silicene,²⁷-²⁹ siloxene,³⁰-³² germanene,³³-³⁶ stanene,³⁷,³⁸ and plumbene³⁹ belonging to group-IVA are verified by theoretical and experimental results, rendering them potential candidates for future nanodevices. The research experience of graphene not only provides enough strategies for exfoliating layered vdWs materials, but also unleashes transfer and characterization of few and single layers. As cousins of graphene, they have also emerged with increasing research interests due to similar synthetic methods, structures, properties, and applications (Figure 1). However, all of them can readily react with oxygen in ambient air, making them more unstable compared with graphene, which inevitably limits their usage toward fundamental research and academic

![Image of Periodic Table of Elements]

**Figure 1** The position of selected group-IV elements in periodic table
applications. Therefore, the restricted methods for synthesizing graphene analogues (silicene, siloxene, germanene, stanene, and plumbene) seem to be much more challenging and difficult. Motivated by this dilemma, these 2D nanosheets, derived from group-IVA elements (Si, Ge, Sn, Pb), have been successfully synthesized by physical and chemical methods as well as played unique and irreplaceable roles in smart electronics, energy storage, and conversion devices. They have grown into new members of the 2D materials and enabled fundamental knowledge of the 2D materials beyond graphene to flourish.

Even though many researchers have reviewed the preparation, characterization, and application of 2D materials, existing articles still lack a comprehensive and systematic overview of 2D group-IV materials. Herein, we present a detailed review that introduces the recent advances of 2D group-IV materials beyond graphene. Initially, we will outline various classes of 2D group-IV materials, as well as highlight layered structures and synthesis approaches based on mechanical and chemical exfoliation, chemical vapor deposition (CVD), and molecular beam epitaxy. Furthermore, some recent progress on their broad applications involving batteries, capacitors, and moist electric generator are reviewed. Finally, we will give a perspective on 2D group-IV materials applied in future electronic and energy devices.

2 | SYNTHESIS AND STRUCTURES OF 2D GROUP-IV MATERIALS

2.1 | Production of graphene

2.1.1 | Chemical vapor deposition

The first single-layer high-quality graphene was achieved through micromechanical cleavage of stacked bulk graphite using scotch tape and then deposited onto a silicon substrate. Nevertheless, the throughput and yield of this method are big obstacles to get large-area and uniform graphene, which shows great promise for its applications in different fields.

CVD is an alternative route to realize large-area uniform polycrystalline graphene employing transition metal foils and films using gases containing carbon as graphene precursors at a certain deposition temperature (Figure 2A,B). Besides, as-obtained graphene typically needs to be transferred from one support to another desired surface (Figure 2C,D). Less stringent experimental conditions are the dominant trend to the growth of graphene with simple transfer process and low-temperature growth on arbitrary surfaces significant to reduce energy consumption. Fazio et al reported the single-layer graphene

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**FIGURE 2** A, Scanning electron microscope (SEM) image of graphene grown on a copper foil. B, High-resolution SEM image of graphene. Inset: illustrating transmission electron microscope images of folded graphene. (C and D) Graphene films transferred onto a SiO$_2$/Si substrate and a glass plate. Reproduced with permission: Copyright 2009, the American Association for the Advancement of Science.
prepared by CVD and wet transfer on Si/SiO₂ substrate, which was subsequently encapsulated in hexagonal boron nitride. The high mobilities up to 70,000 cm² V⁻¹ s⁻¹ at room temperature and greater than 120,000 cm² V⁻¹ s⁻¹ at 9 K are achieved via combined encapsulation and interface cleaning. These are the best performance among the wet-transferred graphene and comparable to those of dry-transferred samples. Based on available methods, the procedure of synthesis is efficiently simplified and improved. Wu et al. developed a new strategy that adopts the vdWs epitaxy to grow graphene on different Cu faces. Because a strong binding exists between as-prepared graphene and the metal substrate under a hydrogen-absent atmosphere, it results in graphene growth in energetically preferable configurations.

### 2.1.2 Molecular beam epitaxy on silicon carbide

Molecular beam epitaxial growth of graphene on silicon carbide has been widely employed to fabricate uniform and wafer-size graphene by sublimating Si atoms, thus forming graphene either on the surfaces of silicon or carbon. Hu et al. designed a defect engineering method to epitaxially grow graphene on SiC(0001). They found that Bi atoms could contribute to the formation of single defects and defect clusters, which dynamically tune the electronic, mechanical, and chemical properties of graphene. But the expensive cost of silicon carbide wafer and high-temperature synthesis would probably be the main limitations to this technique, which is incompatible with modern microelectronic technology and energy saving.

### 2.1.3 Chemical reduction of graphene oxide

Chemical reduction of graphene oxide (GO) has been considered as a simple and convenient method for low-cost, large-scale production of graphene, which has a uniform thickness with the morphology single-layer or bilayer. This technique involves the full exfoliation of graphite into single-layer graphene oxide and subsequently chemically reduce the graphene oxide to graphene. Many abundant functional groups such as epoxide, hydroxyl, carbonyl, and carboxyl are introduced simultaneously on the edges and in the graphene plane. Furthermore, the obtained graphene nanosheets can be conveniently deposited on arbitrary substrates, thus facilitating their potential applications in energy storage and conversion devices.

### 2.1.4 Other methods for producing graphene

There are also a variety of other methods to fabricate graphene while they are unlikely to meet the requirement of mass synthesis for graphene. Electrochemical exfoliation
of graphite is a rapid and effective tool to synthesize high-quality graphene in the presence of dispersants. In this process, graphene is prepared in a two-electrode system, which consists of graphite foil as a working anode, Pt or graphite foil as a counter cathode and ammonium sulfate aqueous solution as electrolyte. Yang et al. developed a scalable exfoliation approach for large-area production of high-quality graphene with high yield, low defects, great solution-processability, and excellent electronic properties (Figure 3). The exfoliation process occurred at both graphite electrodes, enabling a high production rate of graphene. Furthermore, an arc discharge method employing high-temperature plasma has been used to grow graphene with good crystallinity and high thermal stability.

2.2 | Production of silicene and siloxene

2.2.1 | Epitaxial growth of silicene

Silicene, a 2D honeycomb structure of silicon atoms, was epitaxially deposited on a Ag(111) surface under ultra-high vacuum for the first time. It has been proven that silicene can also be successfully created on other clean substrates such as Ir, MoS₂, ZrC, and ZrBr₂ which are treated with argon ion sputtering and high-temperature annealing before using. Huang et al. used a Ru(0001) substrate to grow silicene nanoribbons. When increasing Si coverage, a honeycomb morphology of silicene could form under tension.

2.2.2 | Solid-state reaction method for silicene

Silica fume and magnesium (Mg) powder as starting materials were mixed together and then heated to a high temperature to synthesize silicene (Figure 4). As-prepared silicene flowers were further employed as lithium battery anodes, which exhibited extraordinary electrochemical performance. The feasibility of this technique endows great potential for the preparation of silicene.

2.2.3 | Wet-chemical exfoliation of silicene

Wet-chemical exfoliation is a mild and green method to transform 2D planar materials into freestanding nanosheets. Few-layered silicene as the silicon-based biodegradable tumor nanomedicine was peeled from the layered binary silicide CaSi₂ (Figure 5). It has merits of inherent high biocompatibility with human body, superior photothermal therapeutic capacity, and desirable biodegradability. Wet-chemical exfoliation is an exciting way to create scalable production of high-quality single-layered or few-layered silicene, which shows intriguing promise for biomedical applications and smart electronics.

2.2.4 | Electrochemical exfoliation of silicene

Electrochemical exfoliation of silicene has been proposed by Zhang et al. through a top-down lithiation and delithiation process. Ball-milled silicon nanopowders working as active materials were assembled into a Li-ion battery. After lithiation, lithiated Si was washed with deionized water or various alcohols to render 2D silicene.

2.2.5 | Production of siloxene

Deintercalation of calcium from calcium silicide in HCl solution is widely adopted to prepare siloxene. Siloxene, a 2D green-yellow nanosheet, is

![FIGURE 4](image-url) A, Scanning electron microscope image, (B) transmission electron microscope image, and (C) selected area electron diffraction pattern of silicene, respectively. Reproduced with permission: Copyright 2017, American Chemical Society.
absolutely metastable in air atmosphere. Moreover, heat, moisture, and oxygen will transform it into more disordered structure. Nakano et al. demonstrated that relatively monodisperse nanosheets of siloxene could be produced by liquid-phase exfoliation of a layered silicon compound (Figure 6). The thickness and length of the resulting nanosheets were much smaller than those of previously reported silicon nanoparticles.

### 2.3 Production of germanene

#### 2.3.1 Epitaxial growth of germanene

The emergence of 2D monoelemental germanene that possesses a low-buckled honeycomb structure enlarges the members of 2D-Xenes family. Theoretical and experimental investigations on germanene were both successfully verified. Germanene that holds
appealing physical properties has been grown on a variety of substrates.$^{33-36}$ Similar to silicene, germanene is not air-stable, which is a major obstacle to numerous fields of application.

Yuhara et al.$^{76}$ verified that the epitaxial growth of large-scale germanene nanosheets could be realized on Ag(111) thin films on Ge(111) by a segregation method, which is a technically convenient way to prepare 2D materials.

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**FIGURE 6** A, Transmission electron microscope image, (B) selected area electron diffraction pattern, (C) schematic diagram of siloxene. Reproduced with permission: Copyright 2005, Royal Society of Chemistry.$^{30}$

**FIGURE 7** A, The preparation procedures of germanene quantum dots. B, Transmission electron microscope image and (c) atomic-force microscopy image of germanene quantum dots. Reproduced with permission: Copyright 2019, Wiley-VCH.$^{77}$
2.3.2 | Liquid-phase exfoliation of germanene

Harsh reaction conditions and huge chemical costs apparently restrict the development and application of germanene. Liquid-phase exfoliation with the aid of sonication is a perfect choice to simply and massively manufacture germanene. Ouyang et al.\(^{77}\) presented a simple top-down approach in which germanium power splits into ultrasmall germanene quantum dots (Figure 7). The prepared uniform germanene quantum dots were employed as a photothermal agent, exhibiting outstanding photothermal conversion efficacy, superior stability, and excellent biocompatibility.

2.4 | Production of stanene

2.4.1 | Epitaxial growth of stanene

As inspired by the great success of graphene, the 2D group-IV materials including silicene, germanene, stanene, and plumbene have received enormous research attention owing to their exceptional physical properties. Stanene, a graphene-analogous material with tunable topological states and sizeable bandgap, has been successfully realized using molecular beam epitaxy by Zhu et al.\(^{78}\) (Figure 8). The synthesis of stanene will facilitate the exploration and investigation of other related materials.

2.4.2 | Liquid-phase exfoliation of stanene

Benefitting from the experience of graphene, stanene can be exfoliated by liquid-phase exfoliation, which is a powerful and promising approach for mass production. Ma et al.\(^{79}\) established a facile and feasible dealloying strategy to fabricate few-layer stanene. First, a high-temperature solid-state reaction of Li film and Sn powder was carried out to prepare layered precursor Li\(_2\)Sn\(_2\). Then, by diffusing hydrogen bubbles into the Li\(_2\)Sn\(_2\) aqueous solution, the bonds between biatomic layers were disturbed and destroyed. Finally, the disperse 2D stanene was obtained through sonication and filtration.

2.5 | Production of plumbene

Although plumbene is theoretically predicted to exist, its realization remains a big challenge. The tremendous progress in plumbene was recently made by Yuhara et al.\(^{39}\) They epitaxially grew the planar honeycomb structure of plumbene on a Pd\(_{1-x}\)Pb\(_x\)(111) alloy surface by segregation (Figure 9). Its average size could be dynamically tuned with the Pb concentration of the Pd\(_{1-x}\)Pb\(_x\)(111) alloy. As the last group-IVA cousin of graphene, the growth of plumbene needs to be further explored in science and technology.

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**FIGURE 8**  A. The crystal structure of stanene. B. Reflected high energy electron diffraction pattern of stanene film. C. Large-scale scanning tunneling microscope image of stanene film. D. Atomic structure of stanene. Reproduced with permission: Copyright 2015, Nature Publishing Group.\(^{78}\)
3 | THE VERSATILE APPLICATIONS OF 2D GROUP-IVA MATERIALS

In terms of the huge consumption of fossil fuel, environmental issues are simultaneously rising up and need to be urgently addressed. It is really necessary for energy and environmental security of our society to seek highly efficient renewable energy technologies such as batteries, capacitors, moist electric generators. Extraordinary features of 2D group-IVA materials are that they exhibit high specific surface area, superior intrinsic electrical and thermal conductivity, excellent chemical and mechanical stability, which hold considerable potential in the field of advanced photonic and electronic devices.

Table 1 Summary of the electrochemical performance of anodes based on two-dimensional materials of group-IVA

| Anode                  | First discharge specific capacity | Current density | Retention %/cycles | References |
|------------------------|----------------------------------|-----------------|--------------------|------------|
| Mn$_3$O$_4$/graphene   | 930 mAh g$^{-1}$                  | 100 mA g$^{-1}$ | 73.1/200           | [80]       |
| N-doped graphene-Li   | 156.1 mAh g$^{-1}$               | 0.2 C           | 87.8/500           | [81]       |
| Al$_2$O$_3$/graphene   | 145 mAh g$^{-1}$                 | 0.5 A g$^{-1}$  | 82.9/500           | [82]       |
| Al$_2$O$_3$/graphene   | 156 mAh g$^{-1}$                 | 2 A g$^{-1}$    | 93/6000            | [83]       |
| Li$_x$Si/graphene      | 2.45 mAh cm$^{-2}$               | 1 mA cm$^{-2}$  | 98/400             | [84]       |
| Phosphorene/graphene   | 2441 mAh g$^{-1}$               | 8 A g$^{-1}$    | 59.4/100           | [85]       |
| NiCo$_2$S$_4$/graphene | ...                              | 200 mA g$^{-1}$ | ...                | [86]       |
| Zn/graphene            | 0.85 mAh cm$^{-2}$               | 8 mA cm$^{-2}$  | 62/1000            | [87]       |
| Silicene               | 553 mAh g$^{-1}$                 | 1.0 A g$^{-1}$  | 107/1800           | [88]       |
| Siloxene               | 3900 mAh g$^{-1}$                | C/20            | 47/58              | [89]       |
| Stanene                | 60 mAh g$^{-1}$                  | 4761 mA g$^{-1}$| 100/900           | [79]       |

3.1 | Batteries

There is an ever-growing demand for portable and wearable electronic devices powered by metal ion batteries with high energy density. Metal ion batteries have become research hotspots over the past decades in the account of their tremendous potential to be commercially available (Table 1). But, the lack of suitable electrode materials strictly hinders the development of metal-ion batteries. Graphene, a class of superior thermal and electrical conductors, can not only act as a conductive filler but also form the desirable nanocomposite electrode structures in conjunction with carbon nanotubes, transition metal oxides, and so forth to enhance ion infusion, electron transfer, and alleviate the volume

![Figure 9](image-url) A, Low-energy electron diffraction pattern, (B) large-scale scanning tunneling microscope (STM) image, and (c) atomically resolved STM image of plumbene. Reproduced with permission: Copyright 2019, Wiley-VCH. 39
The strategy for the feasible nanosstructured assembly of a three-dimensional porous graphene/niobia (Nb₂O₅) composite was applied by Sun et al.¹⁸³ to prepare the 3D electrode architecture delivering high areal capacity and high-rate capability at practical levels of mass loading. Subsequently, Zhao et al.¹⁸⁴ found that densely packed Li,M/graphene foils (M = Si, Sn, or Al) would serve as air-stable and freestanding anodes guaranteeing stable structures and exceptional cyclabilities (Figure 10).

In addition to the ubiquitous energy utilization in lithium-ion batteries, graphene has been explored for sodium and potassium storage counterparts as well as zinc and calcium storage.⁹⁷⁻¹⁰⁶ Ultrathin phosphorene nanosheets coupled with conductive graphene as the anode for sodium-ion battery could perform a competitive specific capacity.⁸⁵ More recently, Xie et al.¹⁰⁶ demonstrated the pyrolysis of metal-organic framework wrapped in graphene oxide followed by sulfidation reaction to synthesize bimetallic sulfide for potassium ion storage, in which an ultrahigh reversible specific capacity and ultralong cycle life were achieved. Later, graphene could determine the homogeneous deposition of a zinc anode, which exhibits smooth morphology and exceptional long-term reversibility at various current densities.⁸⁷

The impressive success of graphene in energy storage and conversion devices has driven the discovery and development of new 2D nanosheets of group-IVA. The strategy of wet-chemical exfoliation was adopted to prepare a high yield of few-layer silicene (Figure 11).⁸⁸ It was found that silicene in Li-ion batteries as anodes delivered an extraordinary specific capacity and an ultralong lifespan. The topotactic synthesis of siloxene has also been examined as silicon-based intercalation electrodes, which suffered from the rapid structure deterioration and capacity fading in Li, Na, and K ion batteries.⁸⁹ A facile and general dealloying method was presented to fabricate metallic buckled stanene nanosheets with favorable accommodation of K atoms.⁹⁷ The high surface areas and unprecedented electronic properties of group-VA nanosheets enable them broad perspectives of future technologies.

### 3.2 Capacitors

Capacitor is a kind of device that can store energy within itself. It possesses high power capability, long lifespan, wide temperature range operation, and so forth.¹⁰⁷⁻¹¹¹ Based on charge storage mechanism, capacitors are

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**Figure 10** A, Schematic illustration of highly stable Li,M/graphene foils in different air conditions. B, The synthesis procedures of a freestanding Li,M/graphene foil. Reproduced with permission: Copyright 2017, Nature Publishing Group.⁸⁴
FIGURE 11  A, Scanning electron microscope images of silicene nanosheets. Inset: the monolayer of silicene. B, Transmission electron microscope image, (C) high-resolution transmission electron microscope image, (D) selected area electron diffraction pattern, and atomic-force microscopy images of silicene. G,H, Cycling performance at 0.1 A g$^{-1}$, and rate performance of silicene. Reproduced with permission: Copyright 2018, Wiley-VCH. 88
divided into electrical double-layer capacitors, in which nanoscopic charge separation occurs at the electrode-electrolyte interface and pseudocapacitors with reversible redox reactions at the electrode-electrolyte interface. Compared with the double-layer capacitor, pseudocapacitor can deliver a higher specific capacitance because of the Faradaic reactions of pseudocapacitive materials such as redox oxides and polymers.\textsuperscript{112,113} Recently, many efforts have been dedicated to achieving high power and energy density. There are two main remarkable methods to reach this goal. One is to utilize high surface area and superior conductivity of carbon nanomaterials with an ordered structure as electrodes whereas the other is to combine pseudocapacitive materials with carbon nanomaterials. Graphene is an outstanding candidate with accessible ion diffusion and faster electron conduction as well as good chemical stability for this application.

A scalable microdroplet-based microfluidic method for designing ZIF-8/graphene/carbon nanotube nanomaterials-derived hierarchical micro-mesoporous carbon frameworks was proposed by Cheng et al.\textsuperscript{114} (Fig. 17). This carbon hybrid exhibited a well-defined core structure, high nitrogen-contained active sites, and a continuous conductive network, which were of benefit for ion diffusion and charge transfer. Additionally, the high-performance supercapacitor with large volumetric energy density which integrated micro-mesoporous carbon framework nanofibers into flexible electrodes was put forward by a microfluidic-blow-spinning approach. The key to improving energy and power density is to incorporate graphene into nanomaterials of pseudocapacitor. The hybrid materials containing graphene and dcapacitive materials (manganese dioxide, ferric oxyhydroxide, and polyaniline) were processed into interdigitated microelectrode materials of micropseudocapacitors using a laser fabrication technique, which displayed a remarkable improved capacitive performance arising from the hierarchical structure.\textsuperscript{112} To further enlarge the range of applications, the demand for deformable, integrated, and miniaturized electronic devices has been exceedingly increasing. Taking full advantage of the direct laser writing technique, Gao et al.\textsuperscript{115} manufactured a series of micro-supercapacitors with distinct geometries on hydrated graphene oxide films (Figure 12). More importantly, the trapped water between graphene oxide simultaneously functioned as the electrolyte and electrode separator. Later, a flexible supercapacitor patterned by laser direct writing on a DVD disc was constructed by El-Kady et al.\textsuperscript{116} The excellent energy storage performance was mainly dominated by fabulous conductivity and high specific surface area of the graphene film.

As discussed regarding the electrochemical performance of graphene, siloxene has emerged as a promising electrode material for capacitors because of its large interlayer spacing and high surface area. Krishnamoorthy et al.\textsuperscript{117} demonstrated that a superior symmetric supercapacitor constructed by siloxene displayed pseudocapacitance that is ascribed to the intercalation/deintercalation of ions (Figure 13).

### 3.3 Moist electric generator

The continuous consumption of finite fossil fuels has induced energy crisis and critical environmental issues. It is reasonable for developing ecofriendly and alternative
technologies to generate power from abundant available and accessible sources including sunlight, wind, water, and so forth. Moist electric generator, emerging as a clean and sustainable device that adsorbs gaseous water molecules in air to generate electricity, has gained unprecedented interests due to the wide distribution of steam. Generally, a representative setup of moist electric generator consists of a pair of electrodes and hygroscopic materials. After being fully infiltrated by water vapor, the device could surprisingly generate a potential between two electrodes, arising from the interaction between water molecules and hygroscopic materials. Remarkably, the integrated devices could be connected in series to reach a desirable output voltage, thereby being enough to power commercial electronics. Benefiting from high special surface area and wide pore size distribution, graphene has played an indispensable role in constructing moist electric generator. First of all, the strategy of partially directional thermal reduction was proposed for moist electric generator to realize an asymmetric porous graphene oxide (GO) membrane with a considerable open-circuit voltage approaching 450 mV in ambient condition. Furthermore, Huang et al. revealed that gradient-reduced GO together with a thick GO layer utilized as hygroscopic materials in the moist electric generator could supply a high voltage of 1.5 V. The heterogeneous configuration that can regulate ion migration contributed to excellent performance in this device. Then, laser processing was chosen to assemble a
series of shape-deformable miniaturized graphene-based moist electric generator with potential applications in special and strict working conditions (Figure 14). 3D deformable planar moist electric generators were easily transformed into plenty of spatial architectures, such as cubic boxes, pyramids, football, and so forth. Despite the achievable ultrahigh output voltage, there is still large scope to promote bigger current in high-performance moist electric generators.

4 | CONCLUSION AND OUTLOOK

In summary, we have given a systematic and comprehensive review regarding general synthesis methods and advanced practical applications of 2D group-IVA materials according to the state-of-the-art research advances. As the emergence of graphene, its exotic properties and rich reserves of group-IVA elements shed light on the engineering of group-IVA 2D nanosheets with expected
and desirable power being realized in novel optoelectronic and thermoelectric devices.

Graphene as a perfect 2D carbon-based material has shown its powerful application potentials in the fields of batteries, supercapacitors, catalysis, moist electric generators, solar vapor generation, and so on. The number of layers in graphene would importantly affect its functions and properties, which are critical requirements for further explorations. It is suggested to be of great importance to find a low-cost, environmental friendly, and large-scale strategy for production of high-quality graphene with controllable thickness, appropriate size and shape. Scalable assembling of graphene will need to be tackled before graphene appears in commercial devices.

Silicene, siloxene, germanene, stanene, and plumbene have been successfully verified by both theoretical and experimental results. Silicene, a significant allotrope of silicon, has a buckled honeycomb lattice structure, which has been fabricated in Si-based electronics. Interestingly, it is found that silicene exhibits comparable conductivity and favorable biological effects of biocompatibility and biodegradation. In addition to widely used epitaxial growth, wet-chemical exfoliation is adopted to synthesize silicene, providing enough opportunities and fundamental bases for a number of applications ranging from energy storage and conversion devices to biomedical nanomedicines. The relationship between silicene and siloxene is similar to the affinity of graphene and GO. Nevertheless, the inherent disadvantage that siloxene is sensitive to light, heat, moisture, and oxygen strictly restrains its development. Going one step further, although the low yields and strict synthesis conditions of germanene, stanene, and plumbene are big obstacles to their widespread utilization, their charming properties of the quantum spin Hall effect, topological insulating behavior, and topological superconductivity still appeal to scientists strongly. We believe that this overview can be a guide for future research and inspire more unique discoveries of 2D group-IVA materials.

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ORCID

Nan Chen http://orcid.org/0000-0002-3105-4509

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**AUTHOR BIOGRAPHIES**

**Qiang Guo** received his master’s degree from Southeast University in 2018. He is currently a PhD candidate at the School of Chemistry and Chemical Engineering in the Beijing Institute of Technology (China) and his current research focuses on 2D materials of group-IVA applied to energy storage and conversion.

**Nan Chen** is currently a professor at the School of Chemistry and Chemical Engineering at the Beijing Institute of Technology (China). He received his bachelor’s degree from China Agricultural University and earned his PhD from the Institute of Chemistry, Chinese Academy of Sciences. His research interests lie in the development of new methods and strategies for fabrication of carbon-based functional materials for various applications.

**Liangti Qu** received his PhD in Chemistry from Tsinghua University (China) in 2004. He is now a professor of Chemistry at Tsinghua University (China) and leads the advanced carbon research group. His research interests in materials chemistry mainly focus on the synthesis, functionalization, and application of nanomaterials with carbon-conjugated structures, including carbon nanotubes, graphene, and conducting polymers.

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