Moving towards the market

2D materials face challenges along the road to commercialization, with increasing efforts being made in order to satisfy industrial needs.

The prehistory of graphene, the single atomic layer of graphite, can be dated back to 160 years ago, when the laminated structure of graphite oxide was recognized[1]. Yet it is only in the past 15 years, after graphene was isolated[2], that we have witnessed a tremendous explosion in research and industrial initiatives on this material.

Fast-paced progress in understanding this 2D form of carbon atoms in a hexagonal lattice also opened up the exploration of 2D materials based on other elements or compounds and exhibiting various lattice configurations[3,4], which cover a wide spectrum of electrical and magnetic properties. Hence, 2D materials have repeatedly been predicted to be able to revolutionize electronics and other industrial sectors. This has motivated scientists, engineers and entrepreneurs to bring them to consumers.

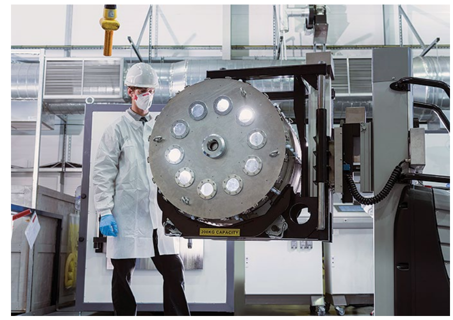
Graphene was the first 2D material to enter the market, and there are now over 350 companies producing related products[5]. We now find it in composites with enhanced mechanical or thermal properties, batteries, inks for printable electronics, photodetectors and some chemical and biological sensors. The next wave of products, such as solar cells, flexible devices, supercapacitors, water filters/desalinators and neural interfaces, is expected to emerge in the following years, as envisioned by the Graphene Flagship[6]. However, the lab-to-fab transition lags behind expectations with slow commercial uptake. Academia and industry are still trying hard to develop reproducible and scalable ways for the synthesis of 2D materials, as well as for their characterization, processing and integration in applications.

A prerequisite for the deployment of 2D materials in applications is the ability to mass-produce them while ensuring satisfactory and reliable performance. In a Comment, Zhongfan Liu and colleagues compare different synthesis techniques, discussing their relative merits in producing graphene for different applications, as well as the respective scale-up issues. Further improvements in controlling the manufacturing processes are certainly needed, and commercialization will also benefit from unified standardization of quality and performance, involving, for instance, an application-specific grading system for the materials produced.

The intrinsic properties and device performance of 2D materials are extremely sensitive to structural disorder that may be generated during synthesis or processing — reproducibility on a large scale can thus hardly be achieved without structural control at the nanoscale. In a Perspective, James Hone and colleagues discuss the possible disorder sources and review the progress in disorder control for graphene and transition metal dichalcogenide-based devices. The development of encapsulation strategies and cleaner device fabrication techniques has brought remarkable performance improvement, yet more work is needed to reveal remaining unknown disorder sources, further reduce intrinsic and extrinsic disorder, and scale up these techniques.

As an example of progress towards this goal, an Article by Libo Gao and colleagues reports a method using only pure elements as precursors to grow high-quality, superconducting 2D transition metal selenides on a wafer scale. The absence of oxygen during the whole process reduces the intrinsic structural disorder of the grown films, which are therefore environmentally stable and are even resistant to some harsh treatments without any protection. As pointed out by Miguel M. Ugeda in a linked News & Views, such improvement in stability and performance reliability should facilitate the use of these strongly correlated 2D materials in fundamental studies and in practical applications.

Moving forward, the next step towards commercialization of devices — particularly optoelectronic devices, where proof-of-concept prototypes based on 2D materials have shown potential to outperform commercial competitors — would be the integration of them with materials and processes well entrenched in the industry. As discussed by Daniel Neumaier and colleagues, the integration of these materials in the Si production line may offer a promising and convenient direction to both take advantage of 2D materials' superior properties and extend the functionalities of currently available Si devices, without requiring substantial changes in fabrication facilities and processes. Their Comment describes strategies to combine graphene devices with the Si complementary metal–oxide–semiconductor platforms and the major hurdles along the way.



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Yet we may lose opportunities to make the most of 2D materials if we think of them as just a replacement for (or addition to) Si or other 3D materials used in contemporary optoelectronics. In fact, the interactions at the 2D–3D interface create sophisticated coupling effects, and hence rich properties that could be harnessed for various applications based on hybrid dimensionalities. These effects are presented by Jeehwan Kim and colleagues in a Review, along with an overview of the techniques to integrate 2D with 3D materials, including transfer and direct growth approaches.

Market demand for 2D materials will only kick in when companies clearly see an added benefit from their actual implementation in a number of end-user products. Having passed the peak of initial hype stemming from prolific fundamental discoveries, the field is seeking to innovate and develop applications and technologies from the customers' perspective. This requires sustained sharing and cooperation from academic labs, standardization and validation institutes, supplier and end-user companies, as well as government agencies, with systematic frameworks connecting all the parties. It is naturally a long-term game for all the stakeholders. ❐

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References

1. Brodie, B. C. *Philos. Trans. R. Soc. A* **149**, 249–259 (1859).
2. Graphene. *Nat. Mater.* https://www.nature.com/collections/xrzkkbbfqg (2007).
3. 2D semiconductors. *Nat. Mater.* https://www.nature.com/collections/kgltwyjtnm (2014).
4. 2D materials beyond graphene. *Nat. Mater.* https://www.nature.com/collections/mcflwjjcyg (2017).
5. *The Global Market for Graphene to 2030* (Future Markets, 2018).
6. *Graphene Flagship Annual Report* (Graphene Falgship, 2018).