https://doi.org/10.1038/s44287-026-00333-3

Electro-exfoliation of two-dimensional materials for printed electronics

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By addressing remaining hurdles, electrochemical lithium-ion intercalation-based exfoliation technology is expected to progress into a scalable and industry-compatible platform for manufacturing high-quality two-dimensional printed electronic materials.

Solution-processable two-dimensional (2D) electronics materials have evolved to a potential cornerstone of modern printed, flexible and large-area electronics[1]. Reliable and large-scale production of such materials has become a shared goal for electronic science and device industry. Direct liquid exfoliation in solution is a powerful addition to the synthetic toolkit[2]. However, its broader application remains limited by the low yield of 2D nanosheets and the toxicity of the organic solvents typically used[3].

As a strong alternative, electro-exfoliation, typified by electrochemical lithium-ion intercalation-based exfoliation, has emerged as a robust production pathway[4]. First demonstrated in 2011 (ref. 5), this technique has matured over 15 years, overcoming successive barriers — particularly in the methodological simplicity, scalability and precise tunability of crystal phases[6–10] — to show clear commercial potential for producing printable 2D electronic materials.

Apart from providing the details of the technology, this article traces the 15-year evolution of this method from early laboratory demonstration to near-commercial readiness, highlighting the scientific and engineering challenges overcome along the way. It also details the remaining hurdles and offers key insights to guide the future development of the technology.

Electrochemical lithium-ion intercalation-based exfoliation technology

The electrochemical lithium-ion intercalation-based exfoliation technology converts layered bulk crystals into solution-processable mono- or few-layer nanosheets. It involves the electrochemical intercalation of lithium ions into layered bulk materials, followed by a mild sonication (exfoliation) process in water and a centrifugal washing treatment for purification[7].

Typically, the electrochemical intercalation of lithium ions is performed in an electrochemical cell, using a copper foil with uniformly coated layered material as the cathode, lithium foil as the anode, and a lithium-ion-containing solution (lithium hexafluorophosphate in a mixture of ethylene carbonate and dimethyl carbonate) as the electrolyte. During discharge, lithium ions are electrochemically inserted into the van der Waals gaps of the layered materials, expanding the interlayer spacing, weakening the interlayer adhesion, and thereby facilitating the delamination of the atomic layers.

After lithium intercalation, the intercalation compound is then collected, dispersed in deionized water and mildly sonicated to produce an opaque nanosheet suspension. The resulting suspension contains unexfoliated fragments, multilayer particles and residual lithium species. Purification is therefore performed by low-speed centrifugation to remove larger particles, followed by repeated high-speed centrifugation washing to remove residual lithium species and other impurities. The purified 2D nanosheets are then redispersed in water or other suitable solvents to form printable inks for storage and subsequent electronic applications.

The past 15-year technology evolution

The electrochemical lithium-ion intercalation-based exfoliation technology was first demonstrated in 2011 (ref. 5). This technique enabled high-yield exfoliation of a wide family of 2D materials, from molybdenum disulfide (MoS_2), tungsten disulfide, titanium disulfide, tantalum disulfide and zirconium disulfide, to graphene[5]. By 2012, the material library expanded further to hexagonal boron nitride, niobium diselenide, tungsten diselenide, antimony triselenide and bismuth tritelluride[6]. Notably, the method achieved unprecedented production yields, with monolayer MoS_2 yields reaching up to 92% (ref. 5). This advance overcame the low efficiency of early liquid exfoliation methods and quickly established the technique as a widely used laboratory tool for preparing 2D nanosheets.

To improve the technological operability, the electrochemical intercalation set-up was redesigned in 2022, where the complex tank-assembled electrochemical cells were replaced with simple coin cells as the core intercalation unit[7]. This redesign greatly improved operational simplicity and reproducibility, supported by a standardized protocol published alongside the advance[7]. The following year, decades of progress were integrated into a unified theoretical framework that identified the origins of uncontrollable phase transitions and highlighted the need for scalable, high-quality manufacturing[8].

Crystal phases of 2D materials, of particular transition metal dichalcogenides (TMDs), govern their electronic properties[8]. For example, 2H-phase MoS_2 behaves as a semiconductor, whereas 1T/1T′-phase MoS_2 shows metallic and semi-metallic character[8]. Uncontrolled phase transition from semiconducting 2H to metallic and semi-metallic 1T/1T′ in this technology has long blocked its electronic applications. This issue was resolved in 2025 by precisely tuning the current and voltage during electrochemical intercalation[9]. Low discharge current density (0.005 A g^{-1}, 0.9 V cutoff) produces pure semiconducting 2H-phase TMD nanosheets, whereas high current density (0.02 A g^{-1}, 0.7 V cutoff) favours semi-metallic 1T′-phase nanosheets. This level of control enables the on-demand synthesis of 2D materials with tailored electronic properties.

With phase controllability realized and technical workflow standardized, the technology was advanced towards large-scale manufacturing of 2D materials. In 2026, the electrochemical intercalation set-up was upgraded from coin-cell to pouch-cell modules[10]. This upgrade lifted production capacity from milligrams to grams, and the modular design enabled simple linear scaling. As a result, kilogram-scale manufacturing has become feasible, opening a realistic path to

large-volume, low-cost supply of high-quality 2D electronic materials.

Remaining technical hurdles

Despite major progress, critical technical challenges still limit the technology's transition to mature materials for next-generation 2D printed, flexible and large-area electronics. Material quality remains a concern. Although precise phase control has been realized[9], mass-produced 2D nanosheets still suffer from defects, surface oxidation and solvent contamination. These issues introduce charge-scattering centres and trap states, reducing carrier mobility and device stability; residues also hinder clean integration and lower device yield. Further advances in low-defect exfoliation, surface passivation and contaminant-free purification will therefore be crucial to improve material quality and device reliability.

Challenge also lies in translating high-quality nanosheets into uniform printed films. Restacking, aggregation and uneven distribution of nanosheets during coating or printing directly cause film inhomogeneity, pinholes and local thickness variations, resulting in inconsistent electrical properties across large areas. Rheology control of the 2D material ink is another challenging issue throughout printing. Strict ink requirements for viscosity, surface tension and nanosheet dimensions further complicate integration with industrial roll-to-roll processes. Unsuitable ink properties cause nozzle clogging, unstable jetting, uneven wetting and non-uniform drying. These issues prevent high-speed, large-area and uniform deposition, limiting throughput, raising production costs and hindering reliable mass manufacturing of flexible and printed 2D electronics. Developing stable ink formulations that simultaneously control nanosheet dispersion and rheological properties will therefore be essential for high-throughput roll-to-roll printing and large-area coating.

Additionally, batch-to-batch consistency and quality standardization remain unmet for industrial manufacturing. Variations in starting materials, intercalation kinetics and processing environments cause fluctuations in layer number, lateral size, phase purity and defect density. Over the next 15 years, standardized production protocols, together with rapid and preferably inline metrology, will be needed to ensure reproducible material quality across batches. Finally, long-term environmental stability is also crucial for practical deployment. Exfoliated nanosheets are sensitive to moisture, oxygen, light and thermal stress. Effective surface passivation, encapsulation and air-stable processing will therefore be important to ensure material and device stability during manufacturing, storage and long-term operation.

Remaining non-technical hurdles

Beyond technology, commercial translation faces additional gaps in funding, industry-accepted metrology standards and supply chains. A major barrier is the early-stage funding gap between basic research and pilot manufacturing. Most support for 2D electro-exfoliation has come from government basic-research grants and university seed funds, which excel at proof-of-concept and lab-scale optimization. However, these programmes rarely cover the high capital costs of pilot manufacturing lines, process scale-up, reliability testing and pre-market validation. Moving from gram-scale demonstrations towards kilogram-scale pilot lines requires investment in larger intercalation systems, purification modules, ink blending equipment and quality-control infrastructure. However, private investment can remain difficult to secure before production reproducibility, cost and market demand are demonstrated at scale. Dedicated translational funding and stronger industrial participation will therefore be important for bridging this lab-to-fab gap.

Missing industry-accepted metrology standards for 2D nanosheet inks is another challenge. Currently, there is no broadly adopted framework for specifying key characteristics of 2D material inks, including layer number, lateral size distribution, phase purity, defect density and surface contamination. Manufacturers cannot set clear ink specifications. End-users cannot predict device-to-device uniformity. Lack of standards blocks quality assurance frameworks, process control and long-term supply contracts. Standardized measurement protocols, material specifications and third-party certification will be needed to establish reliable quality assurance and enable meaningful comparison of materials across suppliers.

Another hurdle is the fragmented supply chain for high-purity raw materials and modular equipment. High-purity layered starting crystals, such as 2H-MoS_2, and specialized electrolytes are not yet supplied at the volume and consistency expected for mature electronic-material manufacturing while scalable intercalation, purification and ink-processing equipment remains highly specialized. These limitations increase costs, extend lead time and make consistent volume production unrealistic. Co-ordinated development across the entire value chain, linking raw-material suppliers, 2D material producers, equipment manufacturers, printing companies and end-users, will be essential for establishing a stable supply chain and accelerating commercial deployment.

Conclusion

By addressing barriers in material quality, film uniformity, ink rheology, standardization, stability and commercial translation — supported by targeted funding, intellectual property development, test beds, supply chain and industry collaboration — this technology could provide a sustainable and scalable route to high-performance 2D electronic inks. These inks could enable flexible circuits, wearable electronics, large-area sensors and printed systems beyond the limits of conventional rigid materials.

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Published online: 17 September 2026

References

1. Kelly, A. G., O'Suilleabhain, D., Gabbett, C. & Coleman, J. N. The electrical conductivity of solution-processed nanosheet networks. *Nat. Rev. Mater.* **7**, 217–234 https://doi.org/10.1038/s41578-021-00386-w (2022).
2. Coleman, J. N. et al. Two-Dimensional Nanosheets Produced by Liquid Exfoliation of Layered Materials. *Science* **331**, 568–571 https://doi.org/10.1126/science.1194975 (2011).
3. Zhang, H. Ultrathin Two-Dimensional Nanomaterials. *ACS Nano* **9**, 9451–9469 https://doi.org/10.1021/acsnano.5b05040 (2015).
4. Zhao, M., Casiraghi, C. & Parvez, K. Electrochemical exfoliation of 2D materials beyond graphene. *Chem. Soc. Rev.* **53**, 3036–3064 https://doi.org/10.1039/D3CS00815K (2024).
5. Zeng, Z. et al. Single-Layer Semiconducting Nanosheets: High-Yield Preparation and Device Fabrication. *Angew. Chem. Int. Ed.* **50**, 11093–11097 https://doi.org/10.1002/anie.201106004 (2011).
6. Zeng, Z. et al. An Effective Method for the Fabrication of Few-Layer-Thick Inorganic Nanosheets. *Angew. Chem. Int. Ed.* **51**, 9052–9056 https://doi.org/10.1002/anie.201204208 (2012).

7. Yang, R. et al. High-yield production of mono- or few-layer transition metal dichalcogenide nanosheets by an electrochemical lithium ion intercalation-based exfoliation method. *Nat. Protoc.* **17**, 358–377 https://doi.org/10.1038/s41596-021-00643-w (2022).
8. Yang, R. et al. Synthesis of atomically thin sheets by the intercalation-based exfoliation of layered materials. *Nat. Synth.* **2**, 101–118 https://doi.org/10.1038/s44160-022-00232-z (2023).
9. Mei, L. et al. Phase-switchable preparation of solution-processable WS_2 mono- or bilayers. *Nat. Synth.* **4**, 303–313 https://doi.org/10.1038/s44160-024-00679-2 (2025).
10. Zhang, Q. et al. Li^+ intercalation chemistry on 2D transition metal dichalcogenides towards phase evolution, scalable production, and application. *Natl Sci. Rev.* **13**, nwag165 https://doi.org/10.1093/nsr/nwag165 (2026).

Acknowledgements
The authors thank financial support from Hong Kong Research Grants Council's Young Collaborative Research Grant (no. C1003-23Y), General Research Fund (nos. 11308923, 11309824 and 11309425), and Hong Kong Innovation and Technology Commission project ITS/192/23.

Competing interests
The authors declare no competing interests.