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RESEARCH ARTICLE

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Multifunctional Electronics Enabled by 2D Materials: From Scalable Synthesis to Device-Level Characterization and Challenges

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Abstract

Two-dimensional (2D) materials like graphene, transition metal dichalcogenides (TMDs), hexagonal boron nitride (h-BN), and MXenes have gained attention as promising materials to develop multifunctional electronics because of their outstanding electrical, optical, and thermal, and mechanical properties. They have high surface-to-volume ratio and atomically thin structure with tunable bandgaps which make them ideal candidates to use in flexible, wearable, transparent, and high-performance electronic systems. This paper gives a detailed overview of current knowledge of scalable synthesis approaches to graphene, such as chemical vapor deposition, liquid-phase exfoliation and bottom-up approaches, as well as state-of-the-art characterization methods that are essential to the study of the structural relationship between property. Moreover, methods of incorporating 2D materials in different device structures including field-effect based transistors, photo-detection devices, memory units and neuromorphic model are also discussed critically. Important issues of uniformity control, contact resistance, interface stability and CMOS compatibility are identified and explained. Lastly, we conclude with future areas of research, such as the design of materials with the assistance of artificial intelligence, large-area production, and the engineering of 2D heterostructures, which will be necessary before 2D materials-based multifunctional electronics can be achieved on a large scale.

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Introduction

The miniaturization of electronic devices and the need for novel functionalities in flexible, wearable, and transparent systems have driven the exploration of new material systems beyond conventional silicon. Two-dimensional (2D) materials, characterized by their atomically thin layered structure, have emerged as a transformative class of materials in this domain. Since the pioneering isolation of graphene in 2004, the family of 2D materials has rapidly expanded to include transition metal dichalcogenides (TMDs) such as MoS_2 and WS_2, insulating hexagonal boron nitride (h-BN), semiconducting black phosphorus (BP), and conductive MXenes. These materials exhibit unique properties including high carrier mobility, mechanical flexibility, tunable bandgap, large surface area, and strong light-matter interaction, making them ideal candidates for multifunctional electronic applications.[1]

The integration of 2D materials into devices such as field-effect transistors (FETs), photodetectors, energy storage systems, and sensors offers several performance advantages. For example, MoS_2 and WS_2 have demonstrated potential as semiconducting channels in ultra-scaled FETs with low subthreshold swing and enhanced electrostatic control.[2] MXenes, on the other hand, exhibit high conductivity and surface functionalization potential, supporting their use in supercapacitors and electromagnetic interference (EMI) shielding.[3]

In spite of their enormous potentials, a number of fundamental hurdles still remain to be overcome before having smooth sailing approaches of bringing 2D

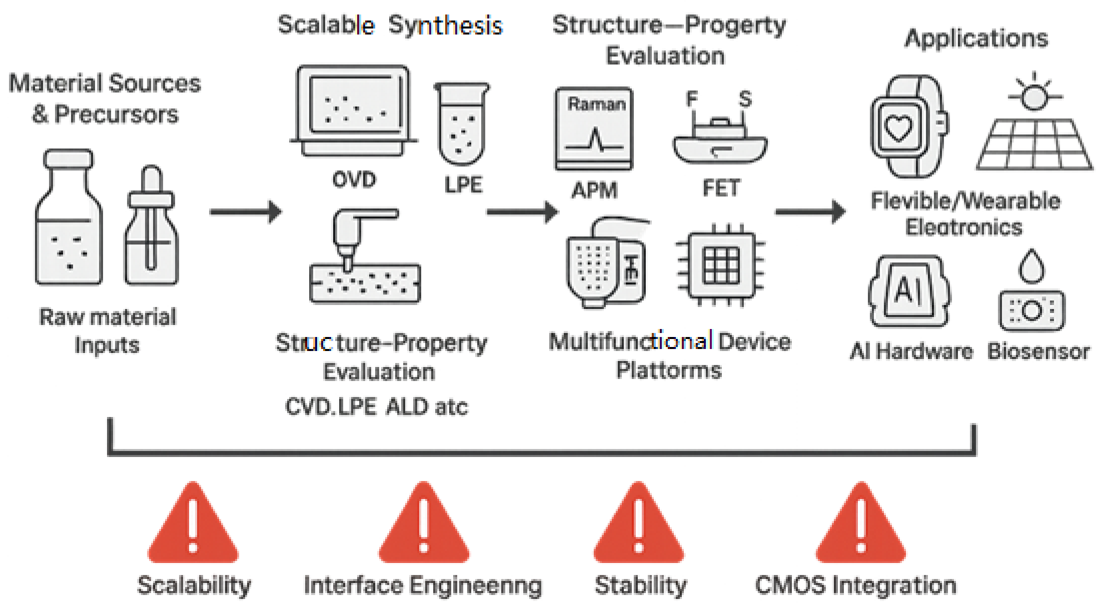

Fig. 1: End-to-End Ecosystem of 2D Material Integration for Multifunctional Electronics

materials discovered in the laboratory to useful device applications. The lack of a uniform and scalable process to produce high-quality and defect-free high-quality 2D materials at large scale is one of the most prominent issues as it is needed to ensure reproducibility in electronic and optical performance over large areas. The other point of significance is the creation of stable and non-destructive mix-up processes through which it is possible to incorporate these materials on various substrates without interfering with their inherent characteristics. Furthermore, a detailed description of the nanoscale structural, electronic, and interfacial properties must be attained with the view to gaining insight in how to optimize the material behavior in complex device architectures. The need to be integrated with the existing silicon based technologies requires also according to CMOS compatible fabrication methods to warrant process compatibility and high mass production expectations.

Finally, there is a major challenge of making 2D-material-based devices reliable and steady both environmentally and in operational capacities over long lifetimes, especially those that could be in flexible and wearable electronics that undergo dynamic mechanical and ambient environments. The proposed study will look into the full development pipeline of multifunctional electronics based on 2D materials, as shown in Figure 1. It includes starting with processing raw precursors to proceeding with the temporal spectrum to higher-level characterization and integration of devices and eventually aims at real applications in the form of flexible electronics and neuromorphic systems, or bio-integrated sensors.

In recent years, synthesis methods chemical vapor deposition (CVD), physical vapor deposition (PVD) and solution-based exfoliation methods have made headway into breakthroughs toward scalable synthesis. But the grain boundary defects, uncontrollable doping, and contamination, between layers still pose a major obstacle.[4] In the same topic, Raman spectroscopy, atomic force microscopy (AFM) and Kelvin probe force microscopy (KPFM) are some of the techniques which are now indispensable in determining the electronic and mechanical functionality of these delicate materials.[5]

The present paper proposes to present a singular and heterogeneous point of view on the synthesis, characterization, and encapsulation of 2D materials to multifunctional electronic platforms. It highlights the technological obstacles that prevent designing them in a large scale commercially and discusses upcoming solutions to those challenges like material design with the help of AI, 2D heterostructures, and the flexible printed electronics sector. By charting out the whole mode of material development to system-level realizations, the work provides insights into the revolutionization capacity and operational issues of 2D-material-based electronics.

Literature Review

Advancements towards two-dimensional (2D) materials have been one of the foundational elements of the next-generation of advancements in electronics.

These include possibilities of multifunctional applications due to their tuneable bandgap, high surface-to-volume ratio, flexibility, and atomically thin geometry which enables possibilities of new things such as flexible electronics, optoelectronics, and neuromorphic systems.

Historical Foundation and Material Families

The discovery of graphene by Novoselov et al.[1] opened up the field of two-dimensional materials by introducing the world to the idea of single-atom-thick crystals. This discovery was soon followed by exploration of other 2D materials like MoS 2 , WS 2 , black phosphorus and h-BN each Cher and unique optical, mechanical and electronic characteristics.[3, 4] Chhowalla et al.[3] underlined the inherent flexibility of transition metal dichalcogenides (TMDs) that have had direct-to-indirect transition bandgaps and thereby are eminently fitting to field-effect transistors and light detectors. The materials can be tailored to specific electronic properties, since they are varied in conduction mechanisms, optical absorption characteristics, and mechanical compliance. A more recent set of 2D materials, namely MXenes are also metallically conductive, can be functionally modified on the surface and are extremely good at EMI shielding,[5] qualifying them as great options in energy storage and high speed information systems.

Scalable Synthesis Techniques and Their Challenges

Mechanical exfoliation is the gold standard in defect free flake production,[6] it is however not scalable and unable to be used industrially. CVD (chemical vapor deposition) is one of the large-area synthesis methods that have become popular in growing MoS 2 and Graphene monolayers.[7] However, factors like grain boundaries, layer discontinuities and contamination incurred in the transfer mechanisms have a strong influence on the performance of the device.

A more recent study by Sharma et al.[9] started a new approach of molten-salt production of scalable 2D semiconducting materials that can be tuned as well. This method provided a higher control over layer uniformity when compared relative to conventional methods of LPE.[8] Nevertheless, reproducibility and compatibility of the interfaces that should be integrated remain to be tested.

As ways of relating to the successful technology of IC integration into practice, 3D ICs and vertical stacking structures sufficiently discussed by Laa and Lim[16] had the potential to become 2D material as the interconnect or active components of small size but high-performance systems in the future.

Advanced Characterization Methods

Detailed description of properties of 2D materials is critical to comprehend physical and functional behaviors thereof. Ferrari et al.[10] gave a baseline Raman spectroscopy blueprint in the investigation of graphene layers and a way to measure strain, doping, and defects. The AFM and XPS methods also enable surface morphology and chemical states probes that become important during synthesis and post-processes.[11] The methods that are attaining prominence in this area are deep learning-based approaches. Kim et al.[12] also suggested a pipeline that incorporates AI to identify 2D material layers in optical microscopy images in short periods of time, thus offering a faster quality controller in the manufacturing settings. Prasath[19] focused on the application of signal filtering at real-time, which can later be applied into sensor interfacing application utilizing 2D materials, especially in the contexts where dynamic response analysis is required in the noisy conditions, such as in a bio-medical monitoring application or an industrial diagnostics one.

Device Integration and Functional Demonstrations

An increasing amount of the available literature is dedicated to incorporating 2D materials into the structure of devices and systems like FETs, memory elements, photodetectors, and neuromorphic circuits. Radisavljevic et.al.[4] demonstrated high-performance MoS 2 based transistors that had superior electrostatic control and low leakage current. Wan et al.[13] have used this to MoS 2 /graphene heterostructures down to broadband photodetection. When addressing the memory applications, Song et al.[14] outlined the possibility of utilizing 2D ferroelectric materials, which can sustain high endurance non-volatile operations. Nevertheless, Fang et al.[15] emphasized that contact engineering and interface doping is still important to realize long-term stability. William et al.[17] wrote about real-time analytics integration into the system of industrial IoT. Such architectures will be very helpful with the 2D-material based sensors with high sensitivity and environmental robustness. Zakaria and Zaki[21] went on to treat the efficiency of communication in vehicular ad hoc networks (VANETs) whereby 2D flexible antennas and sensors might also be used in low-latency sensing platforms.

Hardware and Logic-Level Compatibility

In ASIC applications, Koteshwaramma et al.[18] presented a reversible FFT engine in 5G network applications in high frequency and reconfigurable logic. With low-power switching elements based on 2D materials, it is possible to enable such architectures with reversible computation paradigms. Moreover, adaptive signal processing implemented on edge-AI environments contemplated by Prasath[19] can be interfaced with the possibilities in 2D materials material in tunable analog front-ends of intelligent edge nodes.

Though material growth to multifunctional device integration has already studied all of these domains (synthesis, characterization, or application) and yet hardly had any studies tried to combine all these research areas into one whole pipeline. The majority of reviews are topic-specific (e.g., on a particular material, e.g., graphene or MoS2), or application-specific (e.g., FETs or sensors). This gap has been addressed as dealt with in the current work, which presents an integrative view that bridges the gap between processes at the material level and real-world implementation, such as the use of AI to optimize materials, flexible packaging, and CMOS friendly integration.

Scalable Synthesis Techniques for 2D Materials

Several synthesis methods have been developed for producing high-quality 2D materials at scale, each with specific advantages and trade-offs.

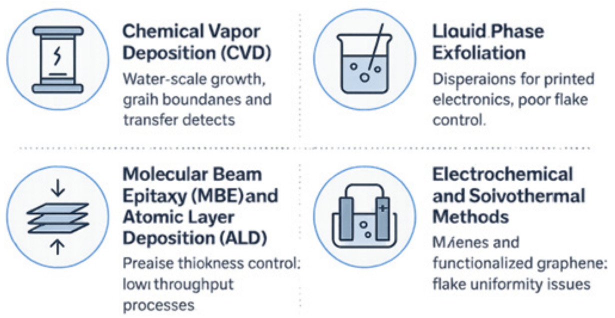

Fig. 2: Scalable Synthesis Techniques for 2D Materials

Overview of scalable synthesis techniques for 2D materials, including CVD, liquid-phase exfoliation, MBE/ALD, and electrochemical/solvothermal methods, with associated benefits and limitations.

Chemical Vapor Deposition (CVD)

The Chemical Vapor Deposition (CVD) process has emerged as a method of synthesis of high-quality and large-area 2D materials including graphene and transition to metal dichalcogenides (TMDs). It has the ability to allow uniform growth at a wafer scale and a controllable thickness and high crystalline quality. Nevertheless, the problem of forming grain boundaries and transfer-induced defects, which are among the critical bottlenecks, and inapplicability in use with bendable substrates continue to prove challenging. Moreover, contaminant and wrinkling can be introduced in processes of transferring devices after growth, which can affect the device performance and reliability.

Liquid Phase Exfoliation

Liquid Phase Exfoliation (LPE) is a scalable, low-cost technology to make dispersions of 2D materials, which would make it amenable to printed and flexible technologies. A technique related to this is ultrasonication or shear mixing of bulk layered crystals in solvents to delaminate them into few-layer flakes. Although LPE has the benefits of being widely used in mass production and ink formulation, it has the drawback of not being able to precisely control the lateral size, number of layers, and the uniformity of the layers thickness of the exfoliated flakes, and thus its usage in precision nanoelectronics remains therefore as a challenge.

Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD)

Another advanced thin-film deposition method is Molecular Beam Epitaxy (MBE) and Atomic Layer Deposition (ALD), which enables atomic scale thickness and stoichiometry control, and high quality film interfaces. The approaches are particularly effective in the growth of complex layered heterostructures, and even van der Waals superlattices. Both MBE and ALD have poor throughput, makes extensive use of equipment that is both expensive and requiring an ultrahigh vacuum environment, and both are highly selective, reducing their potential to scale to larger-scale, commercial production.

Electrochemical and Solvothermal Methods

The electrochemical and solvothermal synthesis methods are developing as green, solution-based, 2D-materials production approaches in which 2D materials like MXenes and functionalized graphene derivatives are created. They are usually run at lower temperatures and may be modified in order to add functional groups in the course of synthesis, which makes the obtained nanosheets more chemically capable. Despite the attractive environmental and economic strength, issues are that the density of the defects, flake characteristics, and compatibility with the industrial manufacturing pipeline is hard to control.

Characterization Techniques for Structure-Property Evaluation

Structural Analysis

The characterization in the form of structure is essential to the knowledge of crystalline quality, thickness, and the density of the defects of the 2D materials. Raman spectrometry is a non-destructive method to determine the number of layers, as well as strain or doping effects, whereas X-ray diffraction (XRD) has been used to get information on layer spacing and phase content. Atomic-resolution transmission electron microscopy (TEM) is used to image lattice structures, grain boundaries, and dislocations, and so can be used to directly appraise material integrity and stacking order.

Electrical Characterization

The electrical conductivity is an essential parameter of determining the feasibility of the 2D materials in electronic schemes. Methods of measuring resistance and conductivity with four-point probe supply precise measurements of the sheet resistance and conductivity thus contact resistance is minimized. Configuration of a field-effect transistor (FET) is a common way to extract important parameters such as carrier mobility, threshold voltage, ON/OFF ratio, and subthreshold swing all of which play critical roles in assessing the potential of 2D materials in high performance switching devices.

Surface and Interface Characterization

2D materials have a high quality surface and interfacial properties which profoundly affect their integration with functional devices. The surface roughness and flake thickness are measured using atomic force microscopy (AFM), whereas the variation of surface potential and work function can be measured by using Kelvin probe force microscopy (KPFM). Also, interfacial X-ray photoelectron spectroscopy (XPS) provides useful chemistry and chemical state data at the interface, which is crucial in informing charge transfer processes and contact design.

Optical and Mechanical Characterization

The multifunctionality of 2D materials can be understood through optical and mechanical characterization mostly in the area of flexible and transparent electronics. Optical absorption properties and bandgap phenomena are interrogated by means of ultraviolet-visible (UV-Vis) and photoluminescence (PL) spectroscopy. In the meantime, nanoindentation and tensile analysis provide accurate values of mechanical strength, Young modulus, and flexibility, which are critical parameters when applying wearable and stretchable devices. Such practices assist in testing the strength and stability of platforms used with 2D materials under stresses caused during operation.

A graphical overview of procedures employed in the research of 2D materials in characterization. Structural analysis is carried out using Raman spectroscopy, XRD, and TEM, electrical characterization using four-point probe and FET-based configurations, interfacial and surface properties are measured using AFM, KPFM, and XPS and optical and mechanical properties are measured using UV-Vis, PL spectroscopy and nanoindentition. Both methods are being mapped to the various material properties which are of interest in multifunctional electronic applications.

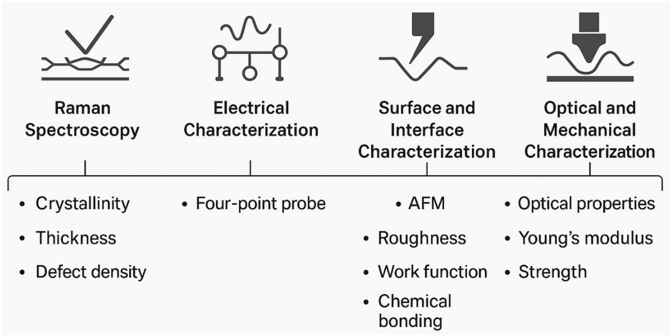

Fig. 3: Characterization Techniques for Evaluating 2D Material Properties

Device-Level Integration and Applications

Transistors and Logic Devices

Two dimensional materials, specifically TMDs like MoS 2, and WS 2 have been shown to exhibit strong potential in use in transistors, with large bandgaps and strong electrostatic control. These materials can be used to make field-effect transistors (FETs) that have large ON/OFF ratio of current, small subthreshold swings, and limited short-cabling effect, which are major properties in next generation low-power logic devices. They can be scaled aggressively due to their ultra-thin geometry and they can therefore be integrated into nanoscale logic and switching devices.

Flexible and Wearable Electronics

Graphene and monolayer MoS 2 are becoming an important part of flexible and stretchable electronics due to their mechanical flexibility, chemical stability and electrically conductive properties. When applied to elastomeric substrates, they make it feasible to create bio-integrated sensors, epidermal electronics, and flexible displays. They are turnkey options in realtime health monitoring, soft robotics, and human-machine interfaces due to their compatibility and survivability in mechanical deformations.

Photodetectors and Solar Cells

Hybrids of 2D/2D materials like MoS 2 / WS 2 and graphene/TMD heterojunctions boast intense light-matter zinteraction and band alignment control, ideal photodetector and solar energy harvesting characteristics with broadband capability. Everything is possible due to these heterostructures being capable of high photoresponsivity, quick response, and wide spectral sensitivity. Their sharper interfaces at the atomic scale and small lattice mismatch facilitates high carrier separation and recombination losses, essential to attaining a high performance optoelectronic device.

Memory and Neuromorphic Devices

Energy-efficient non-volatile memory and neuromorphic computing applications are possible due to unique resistive and ferroelectric switching behavior in the 2D-layered ferroelectrics and oxide-2D hybrids. Multi-level resistance states, low programming voltages and ability to scale down to dense memory arrays are achieved in these materials. On top of that, their capability of synaptic mimicking behavior forces them to become an ideal problem in terms of hardware implementation of brain-inspired computing systems, consequently leading to more progress in edge AI and smart IoT nodes.

Illustrative schematics of device-level integration of 2D materials across various mu0ltifunctional applications The figure highlights:

(a) MoS_2/WS_2-based FET for logic applications,

(b) Graphene-based stretchable sensor embedded in flexible substrate,

(c) 2D/2D heterojunction photodetector with broadband light response, and

(d) Oxide–2D hybrid resistive memory structure. Each schematic emphasizes performance attributes such as low power operation, mechanical flexibility, fast response, and neuromorphic behavior.

Comparison of key performance indicators of various types of devices based on a statistical analysis of the results on the use of 2D materials. These metrics are the field-effect mobility (2), mechanical flexibility (strain%), power consumption (mW) and response time (ms), measured on average according to recent experimental work.

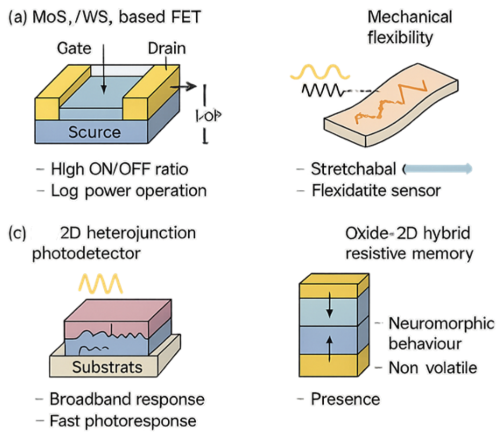

Fig. 4: Device Architectures and Application Areas for 2D Material-Based Electronics

Challenges and Limitations

Even though 2D materials have shown terrific performance in diverse electronic and optoelectronic applications, there still exist some root cause and engineering issues that delay the usage of such materials in the commercial world. These issues include synthesis, interface control, environmental robustness and integration compatibility, which should be exploited to make the manufacturing of the devices reliable and scalable.

Scalability vs. Quality Trade-off

Among the challenges, achieving large area uniform, defect-free monolayer films on large area substrates is one of the most eminent. The most popular scalable method, however, has also become chemical vapor deposition (CVD), which can tend to form grain boundaries, a lack of uniform thickness, and undesirable intentional doping because of inconsistent precursor delivery and the interaction of substrates. Such defects have a direct effect in the carrier mobility, ON/ OFF ratio as well as repeatability of the device. The crucial bottleneck in moving laboratory made large-scale high-quality flakes into industry is closing the gap in between the laboratory and the factory scale.

Table 1: Comparative Performance Metrics of 2D-Material-Based Device Applications

Application Type	Material System	Carrier Mobility ($cm^2/V·s$)	Flexibility (Strain %)	Power Consumption (mW)	Response Time (ms)
FETs / Logic Devices	MoS_2,WS_2	60-200	<1	<5	~0.001
Flexible Sensors	Graphene, MoS_2	~1000	>20	<1	~1
Photodetectors	MoS_2/WS_2Heterostructure	10-30	~5	<10	<0.1
Memory / Neuromorphic	HfO_2 + MoS_2 Hybrid	-	<3	<2	~0.5

Interface Engineering

The 2D devices are metallization-semiconductor contacts under the threat of low charge injection efficiency, high contact resistance, and low contact resistance. Lack of sturdy, replicable technique of contact engineering compromises scalability and reliability of the devices. Moreover, 2D materials exhibit very high sensitivity to the interface conditions as they are the atoms thick such that any contamination, surface imperfections, or dielectric mismatch will have an adverse effect on the overall performance. Phase engineering, van der Waals contacts and edge-contact manufacturing are being researched, although lack reproducibility at any scale.

Environmental Stability

A lot of 2D materials, especially black phosphorus and some TMDs, are volatile with the environmental oxygen and water adsorption, and can degrade at room temperature. Such effects lead to degradation in material structures, mobility and optical response with time. Even fairly immovable materials such as MoS_2 can be subject to hysterisis and shift of threshold voltage under the influence of trapped ambient charges. Alternate methods of encapsulation are emerging, including the atomic layer deposition (ALD) of dielectric barriers, or packaging with inert material, but can add both complexity and processing costs.

Heterointegration and Compatibility

Integrating 2D material into the existing CMOS platform or flexible organic material is quite difficult. There are such problems as thermal budget mismatch, adhesion issues and mechanical delamination, which weaken the long-term operational reliability. Moreover, it is not trivial to maintain the native characteristics of the 2D materials in heterogeneous integration, including their bandgap, mechanical flexibilities, and carrier transport which could be easily altered through the typical production processes involving lithography and etching. To make monolithic 2D-CMOS hybrids to work, low-temperature, transfer-free, and residue-free integration processes need to be developed

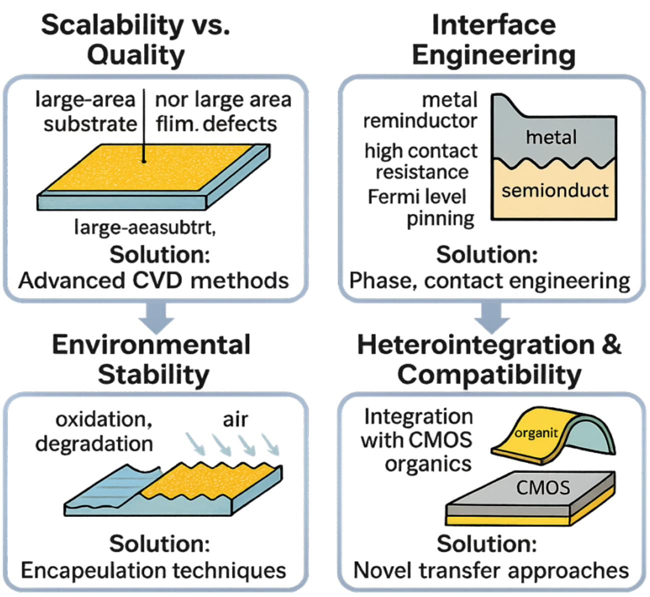

Fig. 5: Major Challenges Across the 2D Material-to-Device Pipeline with Proposed Solutions

Future Directions

In an effort to overcome these constraints and to expedite the realization of 2D materials in multifunctional electronics, a number of visionary research areas are starting to take off. A potentially successful direction is the optimization of synthesis using machine learning, where a data-based model can be used to estimate the optimal set of syntheses, minimize defects in the syntheses, and demonstrate real-time control of synthesis processes like CVD and ALD. In the large scale this can be very good in terms of reproducibility and quality of material. Further, self-healing and bio-inspired 2D materials are also being designed, especially to pursue applications in soft robotics and wearables, where mechanical thresholds and flexibility will play a pivotal role. The self-healing of the structural damage in these materials is possible, or they may emulate biological sensing capabilities, creating new opportunities in bio-integrated electronics. The other essential direction is the integration in heterogeneous form with 3D structures where 2D materials are integrated with silicon or compound semiconductors on either vertical stacks or interposer platforms to expand device density, speed and functionality. Lastly, development of roll to roll process to produce 2D printed electronics will be the key to high throughput/low content production of flex and large area devices. The approach is very well suited to applications in energy harvesting layers, smart packaging and conformable sensors. All these innovations are combined to fill the gap between laboratory-demonstrated prototypes and the industrial implementation of 2D-material-based multifunctional systems.

Conclusion

The 2D materials have risen up as disruptive candidates of the design of multifunctional electronics, with their tremendous electrical, optical, mechanical, and thermal characteristics on atomic level thickness. The paper has provided a thorough account of what is happening in the field of 2D materials today, be it scalable routes of synthesis like CVD, LPE, and molten-salt approaches, sophisticated methods of structural, electrical and interfacial characterization, and lastly to their embedding into practical devices like FETs, photodetectors, flexible sensors, and neuromorphic circuits.

A fine balance between scalability and the quality of the material is one of the key conclusions of this review. Synthesis strategies have come a long way, but overcoming the bottleneck of generating wafer scale, defect-free monolayers still has yet to be accomplished. The key lesson in this case is that interface engineering and surface quality are the major factors in the direct influence of contact resistance, carrier mobility and device performance. Additionally, the issues of environmental stability and heterointegration point to the necessity of coming up with sound encapsulation as well as doping control and CMOS compatible processing schemes.

Because of its integrated view of the problem, the importance of the proposed study is that it unites material-level innovations with challenges occurring at the system-level, and creates a research agenda that requires interdisciplinary research across materials science, nanofabrication, and electronic system design. This work gives an overview of the entire pipeline, a necessary means of solving the challenge of faster technology readiness level (TRL) advances, in the 2D materials field.

Finally, there are a number of future directions that have promising avenues. These involve using AI to optimize processes, creating bio-inspired and self-healing 2D systems, scaling into 3D and heterogeneous integrated silicon designs and roll-to-roll manufacturing of flexible electronics that is scalable. These frontiers have to be bridged not only by maintaining or increasing the innovation that drives experimentation but by the joint development of simulation models, standards, and data-sharing platforms that can support reproducible and high-yield manufacturing.

Finally, 2Ds could reinvent the base of the emerging electronic technol ogy. Nevertheless, they will require appropriate scalability, stability, and integration-enabling strategies that can be attained based on an interdisciplinary approach that maintains equilibrium between core research and application-oriented development.

References

1. Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., ... & Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. *Science*, 306(5696), 666–669. https://doi.org/10.1126/science.1102896
2. Akinwande, D., Petrone, N., & Hone, J. (2014). Two-dimensional flexible nanoelectronics. *Nature Communications*, 5, 5678. https://doi.org/10.1038/ncomms6678
3. Chhowalla, M., Shin, H. S., Eda, G., Li, L. J., Loh, K. P., & Zhang, H. (2013). The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. Nature Chemistry, 5, 263–275. https://doi.org/10.1038/nchem.1589
4. Radisavljevic, B., Radenovic, A., Brivio, J., Giacometti, V., & Kis, A. (2011). Single-layer MoS_2 transistors. Nature Nanotechnology, 6(3), 147–150. https://doi.org/10.1038/nnano.2010.279
5. Naguib, M., Mochalin, V. N., Barsoum, M. W., &Gogotsi, Y. (2014). MXenes: A new family of two-dimensional materials. Advanced Materials, 26(7), 992–1005. https://doi.org/10.1002/adma.201304138
6. Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2008). Measurement of the elastic properties and intrinsic strength of monolayer graphene. Science, 321(5887), 385–388. https://doi.org/10.1126/science.1157996
7. Lin, L., Liu, Y., Halim, U., Ding, M., Liu, Y., Wang, Y., ... & Duan, X. (2018). Controllable growth of large-size monolayer MoS_2 crystals on molten glass. Nature Materials, 17, 129–134. https://doi.org/10.1038/nmat5056
8. Hernandez, Y., Nicolosi, V., Lotya, M., Blighe, F. M., Sun, Z., De, S., ... & Coleman, J. N. (2008). High-yield production of graphene by liquid-phase exfoliation of graphite. Nature Nanotechnology, 3(9), 563–568. https://doi.org/10.1038/nnano.2008.215
9. Sharma, A., Zhang, Y., Wei, C., Wu, J., Wang, Y., He, R., ... & Bao, Q. (2023). Scalable molten-salt synthesis of 2D semiconductors with tunable properties. ACS Nano, 17(2), 1482–1493. https://doi.org/10.1021/acsnano.2c07323
10. Ferrari, A. C., Meyer, J. C., Scardaci, V., Casiraghi, C., Lazzeri, M., Mauri, F., ... & Robertson, J. (2006). Raman spectrum of graphene and graphene layers. Physical Review Letters, 97(18), 187401. https://doi.org/10.1103/PhysRevLett.97.187401
11. Yoon, Y., Ganapathi, K., & Salahuddin, S. (2011). How good can monolayer MoS_2 transistors be? Nano Letters, 11(9), 3768–3773. https://doi.org/10.1021/nl201822c
12. Kim, H., Cho, Y., Ahn, C., Lee, H., & Lee, G. (2020). Deep learning-enabled rapid identification of 2D materials in optical microscopy images. NPJ 2D Materials and Applications, 4(1), 1–7. https://doi.org/10.1038/s41699-020-0163-6
13. Wan, W., Yu, Z., Wang, X., Liu, W., & Wu, Y. (2019). Ultrafast and broadband photodetectors based on 2D materials. Advanced Functional Materials, 29(13), 1902959. https://doi.org/10.1002/adfm.201902959
14. Song, Q., Wang, B., Liu, M., Xiao, C., Sun, W., & Wang, Y. (2021). 2D ferroelectric materials for memory applications.

Small, 17(36), 2102106. https://doi.org/10.1002/smll.202102106

15. Fang, H., Tosun, M., Seol, G., Chang, T. C., Takei, K., Guo, J., &Javey, A. (2013). Degenerate n-doping of few-layer transition metal dichalcogenides by potassium. Nano Letters, 13(5), 1991–1995. https://doi.org/10.1021/nl4007479
16. Laa, T., & Lim, D. T. (2025). 3D ICs for high-performance computing towards design and integration. *Journal of Integrated VLSI, Embedded and Computing Technologies*, 2(1), 1–7. https://doi.org/10.31838/JIVCT/02.01.01
17. William, A., Thomas, B., & Harrison, W. (2025). Real-time data analytics for industrial IoT systems: Edge and cloud computing integration. *Journal of Wireless Sensor Networks and IoT*, 2(2), 26–37.
18. Koteshwaramma, K. C., Vijay, V., Bindusree, V., Kotamraju, S. I., Spandhana, Y., Reddy, B. V. D., ... &Vallabhuni, R. R. (2022). ASIC implementation of an effective reversible R2B FFT for 5G technology using reversible logic. *Journal of VLSI Circuits and Systems*, 4(2), 5–13. https://doi.org/10.31838/jvcs/04.02.02
19. Prasath, C. A. (2025). Adaptive filtering techniques for real-time audio signal enhancement in noisy environments. *National Journal of Signal and Image Processing*, 1(1), 26–33.
20. Zakaria, R., & Zaki, F. M. (2024). Vehicular ad-hoc networks (VANETs) for enhancing road safety and efficiency. *Progress in Electronics and Communication Engineering*, 2(1), 27–38. https://doi.org/10.31838/PECE/02.01.03