सत्यमेव जयते
NITI Aayog

NITI Frontier Tech Hub

FUTURE FRONT

QUARTERLY FRONTIER TECH INSIGHTS

Introduction to 2D Materials

Issue 4 I September 2025

सत्यमेव जयते
NITI Aayog

NITI Frontier Tech Hub

Introduction to
2D Materials

Lead Contributor

INDIAN INSTITUTE OF SCIENCE
भारतीय विज्ञान संस्थान

Foreword

In today's era of digital transformation, the world stands on the cusp of a materials revolution that promises to redefine the horizons many industries including the semiconductor and quantum technology industries. Two-dimensional (2D) materials, characterized by their atomically thin layers and extraordinary electronic, optical, and mechanical properties, have emerged as a beacon of innovation that will power the next wave of technological breakthroughs.

This 4th Issue of Quarterly Insight document, "Introduction to 2D materials" offers a timely and strategic exploration of these disruptive materials. As organizations and nations compete for technological leadership, 2D materials stand out not just for their scientific novelty but for their capacity to enable entirely new device architectures, scalable quantum systems, and previously unimaginable applications—spanning from ultra-fast electronics and flexible devices to advanced sensors and quantum computing platforms.

For India, the rise of 2D materials is both a promising opportunity and a strategic necessity. It calls for building indigenous expertise, fostering robust academia-industry collaboration, and setting up strong frameworks for research, production, and market readiness. At the same time, it's crucial to stay ahead of risks originating from concentrated global supply chains and actively cultivate international alliances to ensure the resilience and sustainability of our innovation ecosystem.

The choices we make today will determine not just technological leadership, but also economic sovereignty and global influence in the decades to come. Let us lead with vision, purpose, and preparedness as we shape the future with 2D materials at its core.

B. V. R. SUBRAHMANYAM
CEO, NITI Aayog

The landscape of materials science is undergoing a transformative shift as two-dimensional (2D) materials, such as graphene, transition metal dichalcogenides (TMDCs), transition from the cutting-edge research lab into the mainstream of semiconductor and quantum technology development. Their remarkable physical properties—including ultra-high carrier mobility, exceptional strength, tuneable electronic band structure, and large-area scalability—enable device innovations that were previously unattainable with traditional bulk materials.

This 4th Issue of Quarterly Insight document comprehensively addresses not only the fundamentals of 2D materials—atomic structure, synthesis routes, and property tuning—but also delves into the challenges and opportunities that define the current ecosystem.

The global race to unlock the potential of 2D materials has triggered intense international competition—driving swift technological progress while also escalating the struggle to secure vital supply chains. The supply and trade of essential elements, such as graphite or transition metals, are now subject to increasing geopolitical scrutiny. Sanctions, regulatory changes, and export controls threaten to impede the free flow of technology and materials—highlighting the necessity for self-reliance, especially for countries like India aspiring to a leading global role. The call to action for technologists clear: Bridge the translation gap from laboratory breakthroughs to scalable, reliable industrial adoption.

DEBJANI GHOSH
Distinguished Fellow, NITI Aayog;
Chief Architect, NITI Frontier Tech Hub

Two-dimensional (2D) materials have emerged as one of the most promising frontiers in the post-silicon era of electronics and quantum technologies. Their atomically thin structures and exceptional electrical, mechanical, and optical properties make them uniquely suited for applications ranging from next generation nanoelectronics and memory devices to quantum computing, neuromorphic systems, and advanced sensing platforms.

Over the past decade, the global scientific and industrial community has made tremendous strides in translating the promise of 2D materials into tangible technologies. Major players such as Intel, TSMC, Samsung, and IMEC have already integrated 2D materials into their long-term technology roadmaps. The message is clear: the future of semiconductors will be defined not just by how far we can push silicon, but by how well we can harness the potential of 2D materials to complement, and eventually redefine, our devices and systems.

India has made commendable contributions to the global 2D materials research landscape. Our academic institutions and national laboratories have delivered breakthroughs in materials synthesis, device prototyping, and system-level innovations. However, in order to move from scientific excellence to technological leadership, a focused, mission-mode effort is now imperative. This must be supported by a national strategy that aligns research with real-world demonstrators, incentivizes industry-academia collaboration, and provides a long-term roadmap for indigenously scaling up this critical technology.

As someone deeply engaged in the development of 2D semiconductor technologies, I believe India stands at a pivotal crossroads. The decisions we make today – about investments, infrastructure, and institutional frameworks – will shape our technological sovereignty for decades to come. This timely article is a call to action for all stakeholders across the government, industry, and research communities.

I hope it inspires the momentum we need to catalyze India’s leadership in the post-silicon world.

PROF. MAYANK SHRIVASTAVA
Indian Institute of Science, Bangalore

EXECUTIVE SUMMARY

Imagine holding a material so unimaginably thin—just about one atom thick, or around 1 nanometer (nm). For scale, 1nm is about 1/80,000 the width of a human hair, or 800,000 times smaller than the tip of a pencil. Despite its thinness, this material is about 200 times stronger than steel and conducts electricity more efficiently than copper.

Picture smartphones that fold like paper yet remain unbreakably resilient, or displays so thin they disappear into the surface, ultra-efficient CPUs and GPUs that run faster and cooler, slashing energy consumption and extending battery life by days. **Welcome to the groundbreaking world of two-dimensional (2D) materials**.

At the forefront are graphene and transition metal dichalcogenides (TMDCs) — one being a single layer of carbon atoms arranged in a flawless hexagonal lattice structure and the other being atomically thin lattice of metal (Mo, W, etc.) and chalcogen (S, Se, etc.) atoms — that have radically expanded the frontiers of materials science.

Other promising 2D materials include hexagonal boron nitride (h-BN) and Xenes such as silicene. When researchers at the University of Manchester first isolated graphene in 2004 using ordinary adhesive tape, they didn't just discover a new material—they sparked a technological revolution poised to reshape everything from electronics to quantum computing. This breakthrough earned them the 2010 Nobel Prize in Physics and paved the way for the identification of more than 700 materials in two-dimensional form.

Why is it important: 2D materials like graphene and transition metal dichalcogenides (TMDCs) are only one atom thick, yet they exhibit properties that could redefine the future of technology. Their unique structure—strong covalent bonding within layers and weak forces between them—gives them:

1. **Exceptional conductivity** – Graphene conducts electricity better than copper and offers unmatched thermal performance.
2. **Mechanical strength and flexibility** – Can stretch up to 20% of its original size without breaking.
3. **Breakthrough semiconductor performance** – TMDCs offer tunable bandgaps and atomically thin channels, enabling post-silicon chip scaling, advanced neuromorphic and memory devices, and heterogeneous chip integration.
4. **Quantum advantage** – These materials host qubits using spin states and quantum dots, making them critical for quantum computing.

Thanks to these attributes, 2D materials are central to the development of next-generation semiconductors, memory devices, quantum technologies, flexible electronics, and advanced energy systems.

Tech giants such as TSMC, Samsung, Intel, and IBM are investing aggressively in 2D material development as they usher in the angstrom-scale transistor era. In quantum computing, these materials offer robust platforms for hosting qubits via spin states and quantum dots—enabling scalable, coherent quantum architectures. Their applications extend far beyond, permeating nearly every frontier of advanced technology.

The transformative promise of 2D materials—from next-gen semiconductors, neuromorphic computing to quantum breakthroughs and more— the global race for leadership in this field has intensified into a high-stakes geopolitical contest. What began as a scientific frontier has evolved into a critical axis of national security, economic competitiveness, and strategic autonomy.

China currently leads the charge, leveraging coordinated policy frameworks, substantial R&D investments, and robust manufacturing infrastructure to dominate 2D materials' technology advancements with similar significant efforts in USA, Europe, Korea and Singapore. As the transformative potential of materials like graphene and transition metal dichalcogenides (TMDs) become increasingly evident, governments worldwide are ramping up their efforts through targeted funding, industrial partnerships, and regulatory strategies—reshaping the global tech power map one atomic layer at a time.

The India Opportunity: For India, 2D Materials represent:

1. A chance to leapfrog into post-silicon semiconductor leadership.
2. An opportunity to build self-reliance in chips, sensors, and quantum technologies.
3. A pathway to capture a share of a multi-trillion-dollar global industry while strengthening defense, AI, and energy security.

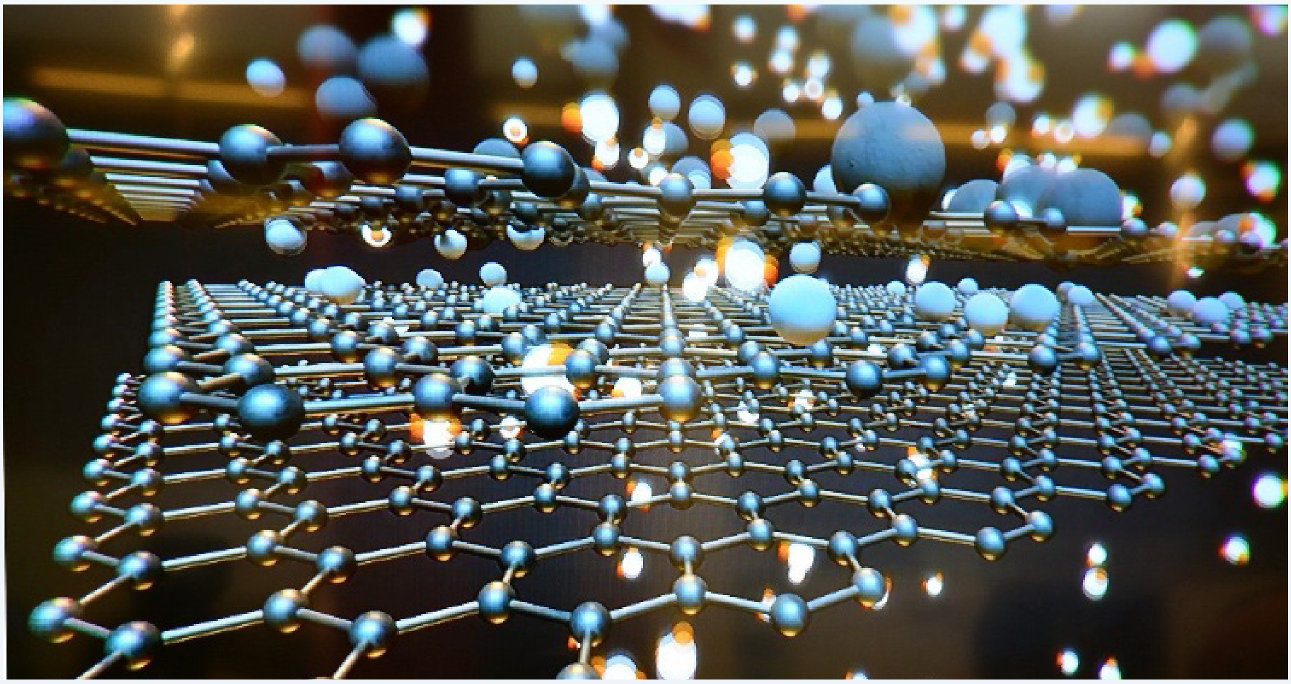
India's success in 2D materials-based technologies will hinge on the coordinated execution of ambitious research proposals, sustained government funding, and integration with broader national technology missions like India Semiconductor Mission.

The convergence of semiconductor policy and 2D materials research presents an rare and timely opportunity for comprehensive technological advancement. With urgency and precision, India can disrupt the global Semicon race and lead in post-silicon technologies. The window of opportunity for India to secure leadership in 2D materials remains open but we need to act with decisive action and high urgency to leapfrog and secure India's place in the global 2D materials race.

SECTION 1: FOUNDATIONS OF 2D MATERIALS

1.1 What are 2D materials

2D materials are crystalline substances with a thickness ranging from one to a few atomic layers, typically less than 1 nanometer (nm). Their atomically thin structure—extending in two dimensions with minimal thickness in the third—imparts unique electronic, optical, and mechanical properties compared to their 3D counterparts.



A representational image of graphene, one of the 2D materials, depicting its one-atom thick structure.

These exceptional properties of 2D materials arise from their unique atomic structure, which enables remarkable strength and electrical efficiency. In materials like graphene, a tightly bonded honeycomb lattice with strong covalent bonds forms a robust, near-perfect structure. This defect-free arrangement distributes forces evenly for exceptional strength and suppresses phonon scattering, enhancing both mechanical and thermal conductivity offering a smooth pathway for electrons, resulting in high electron mobility that powers faster, low-power electronics.

Similarly, exceptional electronic and optoelectronic properties of 2D materials have opened up pathways for next generation nanoelectronics, neuromorphic, memory and quantum technologies. Unlike graphene, many 2D materials have band gaps that can be precisely tuned by changing layer numbers, applying strain, or through chemical modification. This tunability enables custom-designed semiconductor applications.

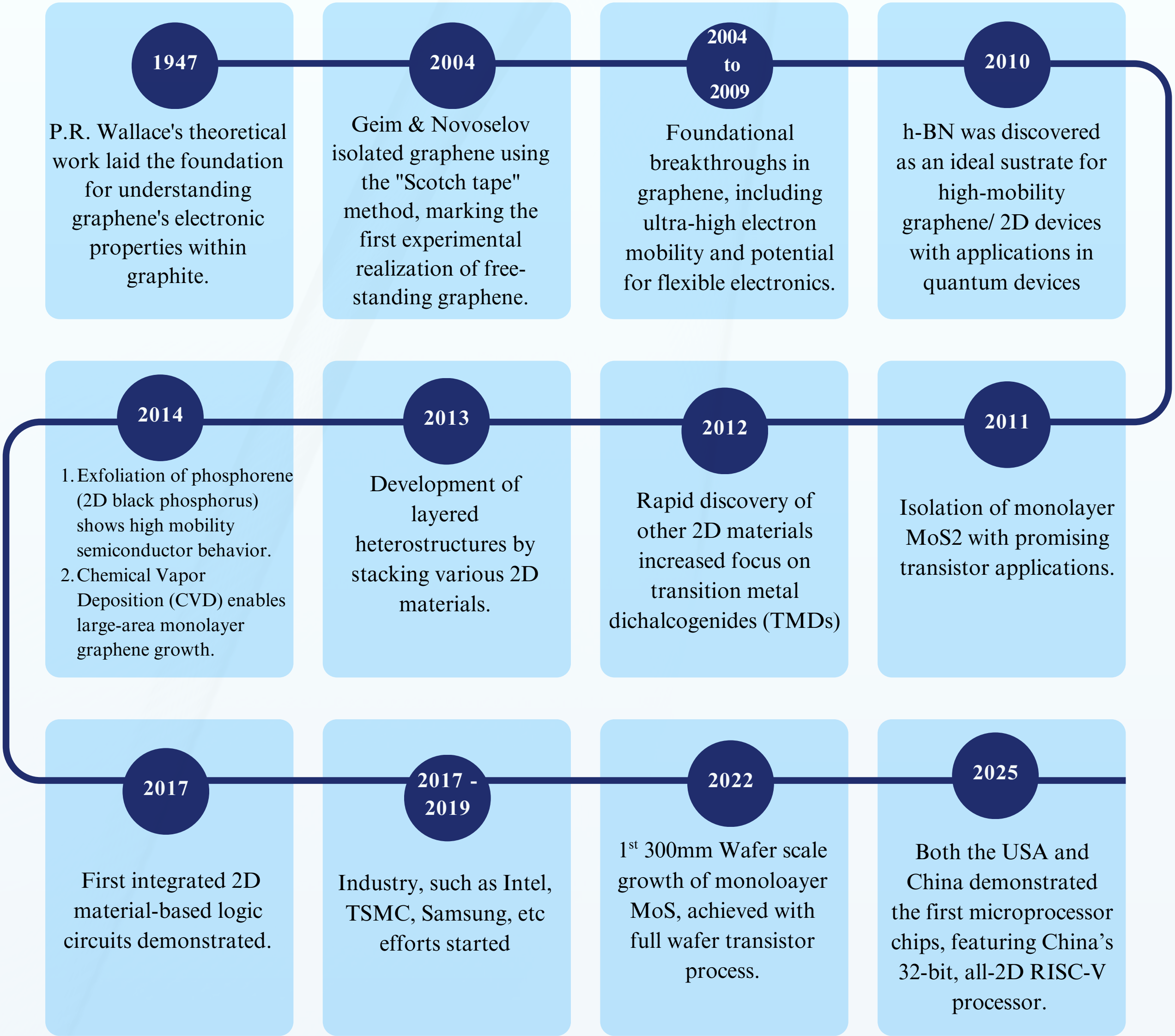
Moreover, the ultrathin nature of the 2D materials creates a high surface-to-volume ratio, greatly enhancing their sensitivity to detect minute environmental or chemical changes, making them ideal for precise sensors in biomedical and environmental applications. Their thin, layered structure also provides mechanical flexibility, enabling innovative applications like bendable screens and wearable/flexible logic devices.

1.2 Major Milestones:

The evolution of 2D materials has unfolded through a series of transformative milestones reflecting both the depth of scientific inquiry and the unprecedented pace of technological advancement in the field.The theoretical groundwork was laid as early as 1947, when P.R. Wallace analyzed the electronic properties of graphite, establishing the conceptual basis for understanding graphene. Yet it took nearly 55 years—until 2004—for this theory to transition into reality, when Geim and Novoselov experimentally isolated monolayer graphene using the now-famous “Scotch tape” method. This discovery, which earned them the Nobel Prize, catalyzed a rapid cascade of foundational research between 2004 and 2009, revealing graphene’s ultra-high electron mobility and potential for high frequency electronics.

By 2010, hexagonal boron nitride (h-BN) emerged as a critical insulating substrate for high-performance 2D devices, including applications in quantum technologies. In 2011, monolayer MoS_2 was isolated, showing transistor-like behavior that sparked global interest in semiconducting transition metal dichalcogenides (TMDCs). The subsequent decade saw explosive growth: from the discovery of numerous TMDCs in 2012, to vertical heterostructure development in 2013, scalable chemical vapor deposition (CVD) of monolayer graphene, and the exfoliation of phosphorene in 2014.

By 2017, integrated 2D material-based logic circuits were demonstrated, and industry leaders such as Intel, TSMC, and Samsung had begun investing in 2D semiconductor research. A major inflection point came in 2022, when 300mm wafer-scale monolayer MoS_2 growth with full transistor processing was achieved. In 2025, the USA and China both announced the world’s first microprocessor chips entirely based on 2D materials, including a 32-bit RISC-V processor from China—marking the beginning of atomically thin computing architectures.



1947

P.R. Wallace's theoretical work laid the foundation for understanding graphene's electronic properties within graphite.

2004

Geim & Novoselov isolated graphene using the "Scotch tape" method, marking the first experimental realization of free-standing graphene.

2004 to 2009

Foundational breakthroughs in graphene, including ultra-high electron mobility and potential for flexible electronics.

2010

h-BN was discovered as an ideal sustrate for high-mobility graphene/ 2D devices with applications in quantum devices

2011

Isolation of monolayer MoS2 with promising transistor applications.

2012

Rapid discovery of other 2D materials increased focus on transition metal dichalcogenides (TMDs)

2013

Development of layered heterostructures by stacking various 2D materials.

2014

1. Exfoliation of phosphorene (2D black phosphorus) shows high mobility semiconductor behavior.
2. Chemical Vapor Deposition (CVD) enables large-area monolayer graphene growth.

2017

First integrated 2D material-based logic circuits demonstrated.

2017 - 2019

Industry, such as Intel, TSMC, Samsung, etc efforts started

2022

1st 300mm Wafer scale growth of monoloayer MoS, achieved with full wafer transistor process.

2025

Both the USA and China demonstrated the first microprocessor chips, featuring China's 32-bit, all-2D RISC-V processor.

Key historical milestones in the development of monolayer-to-few-layer 2D materials and their transition from fundamental discovery to full-chip integration.

When viewed against the historical backdrop of semiconductor development, this pace is extraordinary. Silicon's journey—from its early identification as a semiconductor in the 20th century, to the invention of the first transistor in 1947, the rise of integrated circuits in the 1960s, and the emergence of commercial microprocessors in the 1970s—spanned over five decades. In contrast, 2D materials have transitioned from material discovery to full chip demonstration in less than 20 years.

This acceleration is not coincidental, it reflects how 2D materials have leapfrogged earlier bottlenecks by leveraging decades of innovation in silicon processing, cleanroom infrastructure, and nanoscale device fabrication. As a result, these materials are now poised to disrupt conventional semiconductor paradigms with an unprecedented combination of atomic-scale thickness, superior electrostatics, and compatibility with advanced heterogeneous integration platforms.

SECTION 2: TRANSFORMATIVE APPLICATIONS OF 2D MATERIALS

One of the key attributes of Two-dimensional (2D) materials is that their properties vary significantly based on their thickness and structural form. In particular, monolayer to few-layer 2D materials (typically up to 3–5 atomic layers) exhibit characteristics that are fundamentally distinct from their bulk, polycrystalline, or ink-based counterparts.

Importantly, many of the desirable properties of 2D materials — such as direct bandgaps, high carrier mobility, quantum spin-valley coupling, and atomic flatness — are most pronounced in their monolayer, bilayer and high crystalline forms. These features are critical for next-generation nanoelectronics, neuromorphic computing, spintronic devices, and quantum device architectures.

In contrast, bulk or polycrystalline forms of 2D materials — often used in the form of inks, composites, or membranes — serve entirely different technological domains such as coatings, filtration, and energy storage. While both categories share a common structural ancestry, their use-cases, physical properties, engineering challenges, and industrial ecosystems are entirely distinct.

2.1 Applications of Monolayer to Few-Layer 2D Materials

Monolayer and few-layer 2D materials, such as graphene, MoS_2, WS_2, WSe_2, h-BN, and others, possess atomic thickness, near-perfect crystallinity, and exceptional semiconducting characteristics. Their atomically sharp interfaces, mechanical flexibility, and quantum confinement make them central to a wide array of frontier technologies, as listed below.

2.1.1 Semiconductors and Logic Devices: Monolayer transition metal dichalcogenides (TMDCs) such as MoS_2 and WS_2, exhibit direct bandgaps and atomically thin channels, making them prime candidates for the next generation of semiconductor devices. These materials overcome the electrostatic and short-channel limitations of silicon, allowing continued transistor scaling into the angstrom regime. Their exceptional electrostatic control and atomically sharp interfaces enable high on/off ratios and low leakage currents, critical for future digital logic. Consequently, they are being explored for integration into field-effect transistors (FETs), tunnel-FETs, steep-slope switches, and atomic-layer logic architectures that could push computation beyond the conventional CMOS roadmap.

2.1.2 Neuromorphic and In-Memory Computing: Several TMDCs and heterostructures formed by stacking different 2D materials exhibit unique charge-trap dynamics and memristive switching behavior. These properties make them highly suitable for neuromorphic computing, where analog switching and memory retention are essential to emulate synaptic and neuronal behavior. By leveraging the charge dynamics in these atomically thin layers, researchers have demonstrated synaptic transistors capable of learning functions, energy-efficient edge-AI processors, and non-volatile memory arrays with high endurance and density. In particular, van der Waals heterojunctions composed of TMDC-insulator-metal stacks are being developed for in-memory computing architectures that fuse logic and memory at the hardware level.

2.1.3 Optoelectronics and Photodetectors: The strong light–matter interaction, high exciton binding energies, and tunable direct bandgaps in monolayer TMDCs make them ideal candidates for next-generation optoelectronic devices. These materials enable compact, high-performance components with spectral selectivity spanning the visible to infrared range. Their two-dimensional nature facilitates enhances absorption and facilitate fast carrier extraction, leading to the development of ultrathin photodetectors, light modulators, and phototransistors. Such devices are becoming increasingly relevant for low-power, high-resolution optical imaging, wearable photonic systems, and integrated optical communication platforms- where miniaturization and spectral control are essential.

2.1.4 Quantum and Spin-Valleytronics: Monolayer TMDCs exhibit spin-valley coupling driven by strong spin–orbit interaction and broken inversion symmetry, giving rise to distinct quantum degrees of freedom. These unique bandstructure features enable the encoding of information in valley and spin indices, laying the foundation for spin-valleytronic devices. Furthermore, their ability to confine carriers in atomically thin quantum dots supports qubit realisation in solid-state platforms. Research efforts are leveraging these properties to develop spin qubits, valleytronic logic elements, and single-photon emitters — critical building blocks for quantum communication and quantum computation systems that operate at low dimensions and energy scales.

2.1.5 Heterogeneous and Flexible Integration: The vanishing thickness, mechanical flexibility, and chemical stability of 2D materials enable their direct integration on unconventional substrates and device architectures. These include flexible plastics, transparent substrates, and even CMOS-compatible back-end-of-line (BEOL) layers, enabling novel chip stacking and form factors. This integration capability is critical for developing foldable or conformal logic circuits, transparent electronics, and wearable neuromorphic elements that operate seamlessly with the human body or in constrained environments. The ability to merge logic, sensing, and memory on non-traditional surfaces through atomic-layer materials opens up transformative possibilities in human-machine interfacing and next-generation form-factor computing.

2.2 Applications of Bulk, Polycrystalline, and Ink-Based 2D Materials

In contrast to monolayer systems, bulk or exfoliated forms of 2D materials — including graphene oxide (GO), reduced graphene oxide (rGO), few-layer flakes, and functionalised composites — are used for their chemical surface activity, mechanical strength, thermal stability, and dispersibility, not for logic or quantum functions.

2.2.1 Composites and Structural Materials: In their bulk or few-layered polycrystalline forms, graphene and its derivatives are widely used to enhance the mechanical, thermal, and electrical properties of composite materials. When embedded into polymer, ceramic, or metal matrices, graphene-based additives improve tensile strength, reduce weight, and increase thermal and electrical conductivity. These advantages have led to their integration into high-performance composites for aerospace structures, sporting equipment such as helmets and racquets, and construction materials like concrete and asphalt. Additionally, the functionalization of graphene enhances interfacial bonding within composite systems, enabling more robust and lightweight designs across a wide range of industrial applications.

2.2.2 Energy Storage and Supercapacitors: Reduced graphene oxide (rGO), few-layer graphene flakes, and functionalized TMDCs such as MoS2 are being explored as electrode materials in energy storage technologies due to their high surface area, chemical tunability, and efficient conductive pathways. These materials serve as cathode and anode components in lithium-ion and sodium-ion batteries, enhancing energy density and improving charge–discharge rates. Similarly, their use in supercapacitor electrodes also enables rapid energy storage and retrieval with improved cycling stability. Such innovations are increasingly important in electric vehicle (EV) batteries, portable electronic devices, and stationary grid backup systems- where performance and longevity are critical.

2.2.3 Water Purification and Environmental: Graphene oxide (GO) membranes and layered 2D materials are emerging as highly effective solutions for water purification and environmental remediation. Their ability to form nanoscale channels enables selective molecular sieving, allowing for the removal of salts, heavy metals, and organic contaminants from water. These membranes have demonstrated utility in applications such as desalination, wastewater treatment, and the selective adsorption of pollutants. Furthermore, their use in CO2 capture and air purification systems leverages their high surface area and functional group tunability to interact with and trap targeted environmental species, making them promising candidate for climate-focused and sustainability-driven technologies.

2.2.4 Coatings and Surface Engineering: Bulk graphene and graphene-based materials are extensively used in the formulation of advanced surface coatings. Their exceptional mechanical hardness, chemical inertness, and impermeability to gases and moisture make them ideal candidates for anti-corrosion, anti-fouling, and wear-resistant layers. These coatings are being applied in industries such as marine transport, pipelines, automotive components, and packaging, where durability and environmental resistance are essential. By enhancing the performance of conventional materials, graphene-enriched coatings contribute to reduced maintenance costs and longer service life across a wide range of sectors.

2.3 Distinction Between Monolayer and Bulk Domains

While the term “2D materials” is often used generically, the technological readiness, value chain, and engineering ecosystems of monolayer and bulk forms are fundamentally different:

Aspect	Monolayer to Few-Layer 2D Materials	Bulk / Polycrystalline / Ink-Based Forms
Thickness	1–3 atomic layers	5–100+ layers, aggregates, or flakes
Target Applications	Semiconductors, quantum, optoelectronics	Composites, coatings, energy, filtration
Material State	Pristine, high-mobility crystals	Dispersions, composites, functionalised
Key Properties	Bandgap tunability, quantum effects	Mechanical strength, surface activity
TRL Level	Low (R&D to prototype)	Moderate to high (commercial in coatings)
Value Chain	Device-grade cleanroom infrastructure	Chemical processing, industrial mixing
End Users	Foundries, quantum labs, AI chip makers	Battery OEMs, coatings industries, construction

2.4 Strategic Implications

Both Mono-layer and Bulk form domains offer complementary value. Leadership in monolayer to few-layer 2D materials directly impacts high-value, high-tech sectors like:

1. Logic and memory scaling (beyond Moore’s Law),
2. Artificial Intelligence acceleration,
3. Quantum computing sovereignty,
4. National semiconductor competitiveness.

In contrast, bulk 2D applications align with mature industries, such as materials reinforcement, coatings, and energy-sectors where cost efficiency and volume dominate.

Hence, policy and R&D strategy must treat these two domains as separate but parallel national missions, with unique infrastructure, skillset, and industrial engagement models.

SECTION 3: GLOBAL 2D MATERIALS' TECHNOLOGY/APPLICATION R&D ECOSYSTEM: A COMPREHENSIVE OVERVIEW

This section examines the global landscape of research, development, and commercialization efforts for technologies based on monolayer to few-layer 2D materials, with a focus on semiconducting, quantum, and neuromorphic applications. Unlike bulk forms or composite-grade variants, which are covered in other contexts, mono-to-few-layer 2D materials demand a distinct ecosystem—spanning cleanroom infrastructure, atomically precise material growth/synthesis, wafer-scale integration, and advanced device architectures. As these technologies transition from laboratory discoveries to real world deployment, countries and corporations are mobilizing dedicated programs and investments. This section outlines how global leaders are shaping this transition through policy frameworks, supply chain strategies, flagship programs, and economic projections. The aim is to map the readiness, momentum, and strategic intent surrounding these materials—not just as scientific curiosities, but as enablers of future-defining industries.

3.1 Market Dynamics

The mono-to-few-layer 2D materials ecosystem—particularly its semiconductor, optoelectronic, and quantum device applications—is at an inflection point where fundamental research is beginning to translate into early-stage technology demonstrators. While the current market size for monolayer 2D materials is modest due to the lack of scalable manufacturing and integration technologies, its long-term disruptive potential is significant. By 2035, 2D semiconductors such as transition metal dichalcogenides (TMDs) are projected to occupy niche but critical segments of the semiconductor value chain, especially in logic beyond silicon, flexible electronics, and ultra-low power neuromorphic processors. Various estimates suggest that even a 5%–10% market replacement or co-integration of 2D materials in the global semiconductor market—expected to cross $1.5 trillion by 2035—would translate to a $75–150 billion technology segment. Moreover, new applications such as ultrathin quantum processors, spin-valleytronic memory, and skin-integrated neuromorphic chips are expected to create entirely new verticals, adding an estimated $50–100 billion in adjacent markets not currently served by silicon-based platforms [1], [2].

3.2 Geopolitical Factors and Supply Chain Vulnerabilities

The mono-to-few-layer 2D ecosystem is deeply intertwined with advanced foundry access, precision metrology, high-purity precursors, and lithographic infrastructure—components that are largely controlled by a few nations. This geopolitical control of these assets renders the 2D technology value chain vulnerable to export restrictions, sanctions, and technological blacklisting. For instance, China has made substantial investments in 2D fabs, notably in transition metal dichalcogenide synthesis, but faces potential blockades in advanced patterning tools from ASML and metrology instruments from the U.S. and Japan [4]. Similarly, U.S. strategic controls over gallium and graphite—critical feedstocks for 2D materials—could disrupt multiple countries' supply chains. This techno-strategic fragmentation may either catalyse national self-reliance or lead to technological balkanization, where critical advancements remain siloed behind geopolitical barriers [5].

3.3 Impact of Sanctions and Tariffs

Sanctions and tariff regimes have already begun to shape the future of advanced materials R&D. The U.S. CHIPS and Science Act, along with export controls on semiconductor tools, directly affects the development and scale-up of 2D-based semiconductor technologies. For example, U.S. export restrictions on atomic-layer deposition and ultra-clean chemical precursors have significantly slowed down 2D FET integration efforts in Chinese fabs. Similarly, Chinese retaliatory export licensing on gallium and graphite—both essential for graphene and TMD synthesis—impacts European and American research pipelines [6]. These reciprocal embargoes risk fragmenting the global research ecosystem, reducing access to shared knowledge, foundry services, and critical tools, thereby stifling innovation and collaboration in a domain that fundamentally requires global scientific exchange.

3.4 Leading Countries: R&D, Investment, and Patent Activity

China, the United States, and South Korea are currently leading the global race in mono-to-few-layer 2D technologies. China holds the largest patent portfolio in graphene and TMD-based semiconductors, with over 10,000 2D-related patents filed between 2015 and 2023 [7]. This includes device-level innovations on MoS_2 FETs, photodetectors, and integrated heterostructure circuits. South Korea, led by institutions such as KAIST and Samsung Advanced Institute of Technology, has demonstrated sub-10 nm 2D FETs and monolithic 3D integration using 2D channels. The U.S., through DARPA, NSF, and DOE programs, continues to fund fundamental 2D research in universities like MIT, Stanford, and UC Berkeley, focusing on quantum coherence, valleytronics, and CMOS-compatible 2D integration. Europe, although less aggressive in device scale-up, leads in metrology and modeling tools through organisations such as IMEC and Fraunhofer. These countries are also the primary contributors to flagship roadmaps like the IRDS (International Roadmap for Devices and Systems), where 2D materials are earmarked as key candidates for sub-1 nm nodes [8].

3.5 Indian Scenario

While India has the talent and growing semiconductor ambitions, our efforts in monolayer-to-few layer 2D materials-based technology development is still at a very nascent stage Current research is largely focused on materials synthesis and basic device characterisation, with limited work on wafer-scale integration, heterostructure engineering, and deployable device prototypes.

Countries like the U.S., South Korea, and China have already started integrating 2D semiconductors into their next-generation chip and quantum computing roadmaps. It is of utmost importance for India to launch a dedicated national program for these technologies.

Institutions such as IISc Bangalore have developed early-stage n- and p-type 2D FETs, 2D circuits, memory prototypes, quantum devices, sensors, optoelectronic devices, RF devices, material growth etc. with few IITs also contributing to research in sensors, exfoliated heterostructures and material synthesis, but we need to have an ambitious national program with a 10 year strategic roadmap to build end to end capabilities along the value chain.

With a strong focused effort that aligns talent, research, infrastructure, and policy, we have the opportunity to leapfrog into the global 2D materials race and avoid being locked out of future high value semiconductors and quantum stacks.

3.6 Examples of Global Best Practices

Several countries have launched coordinated national programs that formally recognise the strategic importance of 2D semiconductors. In the United States, the National Science Foundation's "2D Crystal Consortium" supports scalable synthesis and integration pathways for wafer-scale 2D materials, with a focus on device-relevant applications. The European Union's €1 billion Graphene Flagship—one of the largest research initiatives in Europe—has moved beyond materials discovery into system-level integration, targeting flexible electronics, quantum photonics, and advanced sensor systems. China's 14th Five-Year Plan identifies 2D materials as a priority under its "frontier materials and quantum information" agenda, channeling funding through state-backed research and industry consortia. South Korea's "K-Materials Initiative" supports research into foldable and neuromorphic electronics based on 2D semiconductors, and facilitates public-private partnerships for translational R&D. These programs are no longer focused solely on scientific exploration but are foundational pillars of broader national roadmaps for semiconductors, quantum technologies, and strategic autonomy in microelectronics [9], [10].

In parallel with national efforts, several leading global institutions and industrial research centers are establishing cutting-edge programs to commercialise mono-to-few-layer 2D semiconductors. These initiatives span logic scaling, quantum computing, memory, and neuromorphic devices. Global technology leaders including Intel, Samsung, TSMC, and IMEC are actively exploring 2D materials for gate-all-around FETs, quantum dot arrays, and back-end-of-line (BEOL) logic integration. The Graphene Flagship has also established pilot lines across Europe to support end-to-end prototyping of 2D-based electronics. Internationally recognised research centers include:

1. **United Kingdom**: (1) Cambridge Graphene Centre and (2) National Graphene Institute (University of Manchester)
2. **United States**: (1) 2D Crystal Consortium (Penn State) and (2) Center for 2D Materials and Devices (UT Austin)
3. **European Union**: (1) IMEC's 2D Fab (Belgium), (2) CEA-LETI (France, in collaboration with Intel) and (3) 2D Experimental Pilot Line (Germany)
4. **Singapore**: (1) Graphene Research Centre (National University of Singapore) and (2) A*STAR Institute of Materials Research and Engineering
5. **United Arab Emirates**: Research and Innovation Center for Graphene and 2D Materials (RIC-2D), Khalifa University

These institutions are laying the technological foundation for high-throughput synthesis, CMOS integration, and disruptive quantum-classical hybrid devices based on 2D semiconductors. Together, they represent a growing global ecosystem advancing 2D materials from fundamental research to near-industrial scale integration.

SECTION 4: COST OF MISSED OPPORTUNITY

The failure to proactively invest in the R&D and pre-commercialization efforts to build technologies based on mono- to few-layer 2D materials, especially in semiconducting, quantum, and neuromorphic domains, would result in severe and multi-dimensional consequences for India's scientific autonomy, industrial competitiveness, and long-term strategic interests. While India has demonstrated research strength in this emerging domain, global frontrunners such as the United States, China, the European Union, and South Korea are already making decisive advances in TMDCs based semiconductors, wafer-scale 2D integration, and atomic-scale logic and memory platforms. The window to lead, or even catch up, is rapidly narrowing.

Without immediate, mission-mode action, India risks becoming technologically dependent in the very sectors that will define the next generation of electronics and quantum computing. Our electronics and semiconductor sectors may be locked into low-value, legacy nodes, while other nations scale high-margin AI chips, quantum sensors, and neuromorphic architectures using 2D materials. This will not only constrain India's share in the future semiconductor market but also weaken its ability to set global technology standards.

Strategic vulnerabilities would further deepen if India lacks domestic capacity to fabricate or integrate 2D material-based chips, thereby extending our dependence on an already fragile and geopolitically tense supply chain. This is compounded by the growing use of export controls and sanctions by dominant players, leaving late adopters vulnerable to technology access restrictions.

In parallel, the absence of a robust national ecosystem will accelerate the outflow of top-tier scientific talent and weaken India's ability to generate foundational IP in the global 2D innovation race. Without state-backed infrastructure and funding mechanisms, the commercialization pipeline, from lab to foundry, will remain broken, stalling economic value creation and indigenous enterprise development.

While this article has touched briefly on applications of 2D materials in sustainability domains such as energy storage, water purification, and carbon capture, it is important to note that inaction in these areas also undermines India's climate goals and its ambition to lead in green technology exports.

Above all, the opportunity cost of delay is enormous. The market for 2D material-enabled technologies, including atomic-scale logic, ultra-low-power AI hardware, flexible electronics, and secure quantum systems, is projected to expand dramatically over the next decade. Missing this wave will mean lost high-value jobs, stunted SME growth, and an irreversible lag in India's deep-tech industrial capacity.

In today's global techno-industrial landscape, inaction is no longer a neutral stance, it is a strategic regression. Failing to act decisively now will cede economic sovereignty, diminish India's leverage in global standard-setting, and lock the nation out of one of the most transformative technology frontiers of the 21st century.

CONCLUSION

Mono- to few-layer 2D materials have the potential to redefine computing and unlock substantial economic gains by reducing transistor power consumption, enabling energy-efficient AI, and supporting novel computing form factors. Ultra-thin 2D transistors can operate at sub-0.3V threshold voltages, delivering 5–10x lower power dissipation than current FinFETs, while 2D-based synaptic devices in high-density neuromorphic arrays can shrink chip area by over 40% without compromising performance.

These breakthroughs are critical for edge-AI, wearable devices, and quantum-class processors, where efficiency and compactness are key.

To seize this transformative opportunity, India must transition from fragmented research efforts to a coordinated, mission-oriented 2D Materials Strategy that translates foundational science into rapid, high-impact commercialization. The strategy must center around mono- to few-layer 2D materials for semiconductor and quantum technologies, while also laying supportive infrastructure for other promising domains. Key actions include:

1. Establishing National Innovation Hubs with clear strategic mandates and deliverables:
    - Semiconductors & Quantum Technologies: As the core national priority, this hub must focus on 2D materials-based transistor & memory technologies, neuromorphic computing, 2D chips, 2D-based quantum devices, and heterogeneous integration of classical and quantum applications, targeting technological sovereignty and global export leadership.
    - Energy Storage & Thermal Management: Supportive investments should address high-capacity anodes, supercapacitors, and heat spreaders relevant to EVs, grid storage, and portable electronics.
    - Chemical & Biological Technologies: Initiatives in sensors, membrane technologies, and biomedical platforms should be aligned with healthcare, environmental, and national security needs.
2. Prioritizing Indigenous R&D and Scale-Up under the RDI Fund, ensuring mission-aligned funding continuity and a seamless pipeline from discovery to deployment, especially for

atomic-thin electronics and logic components.

3. Accelerating Lab-to-Market Translation by establishing co-located facilities for advanced prototyping, startup incubation, and testing, particularly for wafer-level 2D processing, while creating incentive structures to attract private investment and foster public–private partnerships.
4. Forging Strategic Global Collaborations with leading international platforms such as IMEC, the Graphene Flagship, and the 2D/Graphene centers in UK, Singapore and USA, to access advanced infrastructure, global markets, and design/fabrication know-how, while building long-term sovereign capabilities.
5. Integrating with National Missions such as the India Semiconductor Mission and National Quantum Mission, ensuring that 2D materials-based semiconductor and quantum technologies form a foundational pillar of India's broader technology, economic, and industrial strategy.

For economies investing early, the payoff goes beyond product exports to include energy savings, IP ownership, and strategic independence as silicon scaling approaches its physical limit. Conversely, the cost of inaction is not just economic but strategic. Countries that fail to invest risk permanent dependence on foreign-controlled logic IP, memory platforms, and quantum processors, and may be locked out as the global stack shifts from CMOS to hybrid architectures integrating 2D, photonic, and quantum subsystems.

REFERENCES

[1] Y. Wu et al., "Monolayer 2D Semiconductor Electronics for the Angstrom Era," *Nature Reviews Materials*, vol. 7, pp. 791–808, 2022. [Online]. Available: https://doi.org/10.1038/s41578-022-00421-8

[2] Global Semiconductor Market Forecast, WSTS, Nov. 2023. [Online]. Available: https://www.wsts.org/76/Recent-News-Release

[3] "India Semiconductor Mission: Strategy and Roadmap," MeitY, Govt. of India, 2022. [Online]. Available: https://ism.gov.in/

[4] CSET Report, "China's Investments in 2D Materials for Quantum and Semiconductor Applications," Center for Security and Emerging Technology, 2023. [Online]. Available: https://cset.georgetown.edu/publication/chinas-investments-in-2d-materials/

[5] T. S. Kim, "Supply Chain Risks in Strategic Materials: The Case of 2D Materials," *Nature Materials*, vol. 22, no. 1, pp. 24–26, 2023. [Online]. Available: https://doi.org/10.1038/s41563-022-01361-w

[6] "US, China Trade Restrictions Hit Semiconductor Material Supply Chains," *Nikkei Asia*, Jul. 2023. [Online]. Available: https://asia.nikkei.com/

[7] StatNano, "Patent Analysis of Graphene and 2D Material Technologies," 2023. [Online]. Available: https://statnano.com/

[8] IEEE IRDS™ 2022 Edition, International Roadmap for Devices and Systems, Emerging Research Devices. [Online]. Available: https://irds.ieee.org/

[9] NSF 2D Crystal Consortium (2DCC). [Online]. Available: https://www.2dcc.psu.edu/

[10] Graphene Flagship, European Commission. [Online]. Available: https://graphene-flagship.eu/

[11] S. Li et al., "Atomristor-Based Neuromorphic Computing Using 2D Materials," *Advanced Materials*, vol. 35, no. 4, 2208613, Jan. 2023. [Online]. Available: https://doi.org/10.1002/adma.202208613

सत्यमेव जयते

NITI Aayog