A Review of Design And Integration of Tunable 2D Materials for Advanced Memory Architectures

④

Sankaraiah Guvvala
Hitesh Reddy Chavva
Sesha Maheswaramma Kalluru

Abstract

The rapid advancement of next-generation memory technologies requires materials that offer high charge mobility, ultrafast switching, and superior scalability. Two-dimensional (2D) materials have emerged as strong candidates due to their atomic thickness, tunable electronic structure, and excellent electrochemical stability. In this study, we present the controlled synthesis of high-quality 2D materials—including transition-metal dichalcogenides (TMDs), layered oxides, and graphene-based hybrids—using both solution-phase and chemical vapour deposition methods. Comprehensive structural, morphological, and spectroscopic analyses confirm uniform layer growth, defect modulation, and engineered surface chemistries optimized for memory applications. When integrated into resistive memory and charge-trapping device architectures, these materials exhibit low switching voltages, high ON/OFF ratios, robust endurance, and long retention times. Overall, the findings demonstrate that rationally designed 2D materials hold significant promise as enablers of high-performance, energy-efficient, and scalable memory devices, supporting future developments in neuromorphic and quantum computing.

Sankaraiah Guvvala
Department of Chemistry, Jawaharlal Nehru Technological University Anantapur College of Engineering, Pulivendula, Andhra Pradesh, India. *Email: sankarguvvala@gmail.com*
Hitesh Reddy Chavva
Department of ECE, KSRM College of Engineering, Kadapa, Andhra Pradesh, India.
Sesha Maheswaramma Kalluru
Department of Chemistry, Jawaharlal Nehru Technological University Anantapur College of Engineering, Pulivendula, Andhra Pradesh, India.
Email: kallurumahi.chemistry@jntua.ac.in
Publisher: Anu Books
Book Name : Chemical Sciences at the Nexus of Sustainability: Bridging Disciplines

Keywords: *Two-dimensional (2D) materials, Memory devices, Energy-efficient, High charge mobility and Quantum computing.*

1. Introduction

1.1 Background of Memory Technologies

Modern computing systems rely heavily on memory technologies to store, retrieve, and process data for a variety of uses, including consumer electronics, high-performance computing, and artificial intelligence. For many years, the semiconductor industry has been dominated by conventional memory technologies, such as flash memory, static random-access memory (SRAM), and dynamic random-access memory (DRAM), because of their mature fabrication processes and dependability. However, the need for memory devices that provide faster operation, lower power consumption, higher density, and non-volatility has increased due to the exponential growth of data-centric applications and the slowing of Moore's law [1]. Though there are still issues with material and scalability, new memory concepts like resistive random-access memory (ReRAM), phase-change memory (PCM), and magnetic random-access memory (MRAM) have been proposed to close the performance gap between logic and storage.

1.2 Limitations of Conventional Memory Architectures

Conventional bulk-material-based memory architectures have inherent technological and physical constraints despite ongoing optimization. Due to short-channel effects and interface degradation, aggressive device scaling raises leakage currents, increases power dissipation, decreases endurance, and raises reliability issues [2]. For instance, flash memory has few write/erase cycles and high operating voltages, whereas DRAM needs to be refreshed frequently, which uses a lot of energy. Additionally, data throughput and energy efficiency in traditional architectures are constrained by the von Neumann bottleneck, which is brought on by the physical separation of memory and processing units [3]. The investigation of new materials and device concepts that can enable scalable, low-power, and multifunctional memory solutions has been spurred by these difficulties.

1.3 Emergence of 2D Materials in Nanoelectronics

Because of their atomic-scale thickness, superior electrostatic control, and tunable electrical, optical, and mechanical properties, two-dimensional (2D) materials have become revolutionary building blocks for next-generation nanoelectronics devices. A wide range of 2D materials, such as layered oxides, van der Waals heterostructures, hexagonal boron nitride, and transition metal dichalcogenides (TMDs), have been thoroughly studied since the discovery of graphene [4]. For advanced memory applications like resistive switching, charge-trap memory, and neuromorphic computing, 2D materials are especially appealing due to their defect-sensitive electronic behavior, atomically sharp interfaces, and compatibility with heterogeneous integration [5]. Crucially, new degrees of freedom for customizing memory performance beyond what is possible with bulk materials are provided by the ability to engineer defects, interfaces, and stacking sequences.

1.4 Scope and Objectives of the Review

This review's goal is to offer a thorough and critical evaluation of current developments in the synthesis, design, and integration of tunable 2D materials for sophisticated memory architectures. Key material systems, synthesis methods, and device configurations that facilitate resistive switching, charge storage and synaptic functionality are the main topics of the review. Understanding how material quality, defect engineering, interlayer coupling, and interface control affect memory performance metrics like switching voltage, endurance, retention, and energy efficiency is given special attention. Future research directions toward scalable and low-power 2D-material-based memory technologies are also outlined, along with a critical discussion of current issues, such as device variability, large-area uniformity, and CMOS compatibility. The purpose of this review is to provide material scientists and device engineers working toward the realistic application of 2D materials in next-generation memory systems with a framework for reference.

2. Overview of Advanced Memory Architectures

In computing systems, memory architectures are crucial because they affect system scalability, energy efficiency, and performance. In order to balance trade-offs between speed, volatility, density, and cost, modern memory hierarchies incorporate a variety of memory technologies. For many years, the foundation of computer memory subsystems has been made up of conventional memory technologies like flash memory, static random-access memory (SRAM), and dynamic random-access memory (DRAM). From on-chip caches to main memory and secondary storage, each of these technologies demonstrates unique operational principles and architectural traits that make them appropriate for particular memory hierarchy levels.

2.1 Conventional Memory Technologies (DRAM, SRAM, Flash)

Static Random-Access Memory (SRAM), Because of its low cost per bit and relatively high density, dynamic random-access memory, or DRAM, is the most common type of main memory in computer systems [Figure 1]. DRAM uses a single transistor per cell (1T1C) to access data that is stored as charge in a capacitor. DRAM necessitates periodic refresh cycles to preserve stored data due to charge leaks over time, which increases dynamic power consumption and complicates controller design at advanced technology nodes [3,6]**.** To reduce memory latency and bandwidth limitations, modern DRAM architectures also include multi-bank designs and sophisticated interfaces [7]**.**

Flash memory is a popular non-volatile memory technology for embedded applications and secondary storage is flash memory. Flash memory allows for persistent storage by storing charge on a floating gate or charge trap to hold data even in the event of a power outage. There are two types of flash memories; NAND flash and NOR flash. NAND flash achieves high densities appropriate for solid-state drives, while NOR flash provides faster random reads at the expense of density. In contrast to volatile memories, flash memory has limited endurance and slower writes and erase speeds despite its advantages in non-volatility and storage capacity [3,8]. The established memory hierarchy is made up of these traditional memory technologies, with flash for non-volatile storage, DRAM for main memory, and SRAM for cache at the top. However, the limitations of DRAM refresh overhead, SRAM area inefficiency, and flash write latency have spurred research into emerging memory technologies that combine the speed of SRAM, density of DRAM, and non-volatility of flash in unified or hybrid architectures as scaling challenges grow and data-centric applications proliferate [9,10]**.**

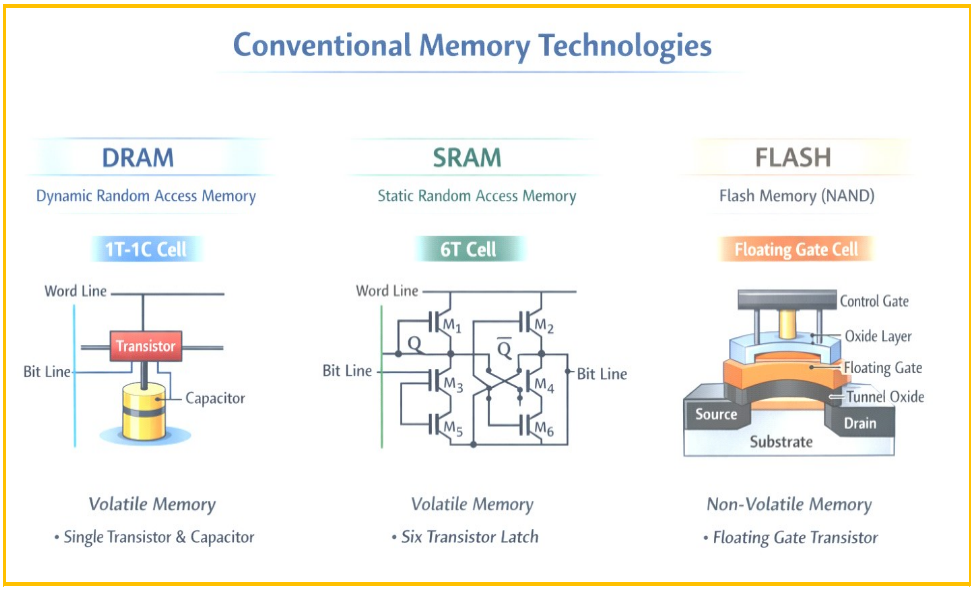

Figure 1: Overview of conventional memory technologies [*Source: Sharma et al., 2023]*

2.2 Emerging Non-Volatile Memories

Because of its straightforward structure, high scalability, low power consumption, and potential for in-memory computing, resistive RAM (ReRAM) continues to show promise as a next-generation non-volatile memory technology. In recent years, research on ReRAM has increased. ReRAM effectively encodes data without requiring constant power by applying voltage pulses to switch between high resistance and low resistance states. It can also support multi-level cell operation for higher storage density [11,12]. For instance, new materials such as zeolitic imidazolate frameworks (ZIF-8) have been studied for thermally stable resistive switching, demonstrating stable retention and tunability essential for neuromorphic computing applications [13,14]. These studies highlight developments in materials and device engineering that improve ReRAM endurance and reliability. Furthermore, forming-free and multi-bit Pd/HfO, -based ReRAM designs show ways to improve performance and reduce energy consumption, which are essential for integration in energy-efficient computing platforms [15,16]. According to market analyses, the ReRAM industry is expected to grow rapidly due to consumer electronics and IoT demands, demonstrating its growing commercial significance [17,18].

Another promising option among new NVMs is Phase Change Memory (PCM), which uses chalcogenide materials' reversible transition between amorphous and crystalline phases to represent data bits. Because of its phase transition mechanism, which provides non-volatility, quick access times, and good retention, PCM is positioned as a leading candidate for storage-class memory in upcoming computer systems [19,20]. With cutting-edge techniques like machine-learning-based adaptive optimization, which dynamically modifies write parameters and reduces energy consumption by up to 63% while enhancing performance metrics, recent research attempts to address important issues like high write energy and limited endurance [21,22]. Due to its dense integration potential, PCM is being thoroughly investigated for applications ranging from datacenter storage to neuromorphic processors [11,23]. The technology's compatibility with standard CMOS processes further highlights its viability.

Magnetic RAM (MRAM) Research focuses on using electron spin to store data with near-instantaneous access speeds, high endurance, and non-volatility. MRAM is appropriate for cache and low-power memory applications because of its key technological implementations, such as spin-orbit torque (SOT-MRAM) and spin-transfer torque (STT-MRAM), which allow switching magnetic states with little energy [9,24]**.** According to recent developments, MRAM may be able to achieve switching speeds that are comparable to SRAM (~1 ns) while retaining non-volatility and data retention for ten years. This would be a major step toward the replacement of conventional volatile memory in future systems [14,25]**.** In addition to its speed and durability, MRAM's radiation tolerance and robustness make it appealing for edge computing, automotive, and aerospace applications where dependability and long-term data storage are essential [14,26]**.**

Ferroelectric RAM (FeRAM) has been thoroughly investigated due to its extremely low power consumption and quick read/write speeds, which are enabled by ferroelectric materials' polarization states. FeRAM is useful in embedded systems and security-sensitive devices like smart cards and Internet of Things electronics because of its high endurance and non-volatility [12]**.** FeRAM's potential role in in-memory computing and energy-efficient architectures is highlighted by cutting-edge research, such as the development of 2T-nC FeRAM cells, which shows how FeRAM can execute logic-in-memory functions with significant performance and energy advantages over conventional DRAM [27]**.** Furthermore, developments in ferroelectric materials, such as doped hafnium oxide, are pushing the limits of memory design for AI and near-memory computing systems by increasing the viability of FeRAM and related ferroelectric field-effect devices [28]**.**

In order to overcome the constraints of current memory hierarchies and open the door for faster, more energy-efficient, and highly scalable non-volatile memory solutions in future computing platforms, resistive RAM, phase change memory, magnetic RAM, and ferroelectric RAM are being optimized. Together, these emerging memories show a dynamic research landscape.

2.3 Requirements for Next-Generation Memory Devices

By achieving strict performance standards across various dimensions, next-generation memory devices are anticipated to transcend the fundamental constraints of traditional memory technologies (e.g., Flash, DRAM). These memories must exhibit high scalability, allowing ultra-high densities that surpass the scaling limits of silicon-based structures—something that conventional three-dimensional designs find difficult to accomplish—to be deemed feasible for use in future computing systems [29]. Another crucial prerequisite is low power consumption, particularly since data-intensive applications like edge computing, mobile platforms, and artificial intelligence require energy economy without compromising performance. In order to guarantee that there is little energy consumption during idle times, this covers both read/write operations and retention at low voltages. Furthermore, in order to facilitate real-time processing and lower latency in system topologies, next-generation memories must offer quick switching speeds that enable quick access on par with or better than existing volatile memories. For devices to be acceptable for both consumer electronics and mission-critical systems, they must be able to withstand repeated programming cycles and consistently maintain recorded information over extended periods of time. Commercial deployment also depends on integration compatibility with current CMOS fabrication processes, which calls for advancements in material synthesis, low-temperature growth strategies, and damage-free transfer approaches to maintain device integrity [30]. Lastly, effective production requires stability and reproducibility at scale, necessitating better characterization and quality control to address variability and performance deterioration caused by defects [25].

3. Two-Dimensional (2d) Materials: An Overview

For next-generation electrical and memory applications, two-dimensional materials—crystalline solids made up of one or a few atomic layers—are especially appealing due to the special qualities that set them apart from their bulk counterparts. Graphene, hexagonal boron nitride (h-BN), and transition metal dichalcogenides like MoS, and WS, are examples of atomically thin 2D materials that offer remarkable electrical, mechanical, and thermal properties, such as strong light-matter interactions in monolayer form, tunable band gaps, and high carrier mobility. These characteristics allow for wide operating temperature ranges, aggressive device scaling with low short-channel effects, and opportunities for van der Waals heterostructure engineering, where atomically smooth interfaces enhance performance and reduce lattice mismatch problems typical of conventional materials [22]. In the context of memory devices, 2D materials offer new resistance switching and charge transport mechanisms that are helpful in memristors, memtransistors, and other non-volatile architectures, providing low switching voltages, lower power consumption, and increased device density [16,31]. Large-scale, high-quality 2D material production is still a major challenge, though; industrial fabrication requires integration with back-end-of-line (BEOL) processes at compatible temperatures, and scalable synthesis techniques like chemical vapour deposition (CVD) must be improved to guarantee uniformity and defect control [26]. Notwithstanding these obstacles, developments in 2D material integration on silicon and hybrid devices show promise for supporting next-generation logic, memory, and neuromorphic computing architectures, which could extend Moore's Law and make ultra-efficient electronic systems possible [14].

3.1 Classification of 2D Materials

The suitability of two-dimensional (2D) materials for electronic, optoelectronic, and memory device applications is determined by their chemical composition, crystal structure, and electrical characteristics. Numerous layered materials have been found since graphene was isolated, each with unique benefits such as strong electrostatic control at atomic thicknesses, mechanical flexibility, and programmable band gaps. Graphene, transition metal dichalcogenides, MXenes, black phosphorus, and hexagonal boron nitride are the main types of 2D materials that are pertinent to improved electronics and memory technologies.

3.1.1 Graphene

Known for its remarkable electrical conductivity, high carrier mobility, mechanical strength, and thermal conductivity, graphene is a single layer of carbon atoms organized in a two-dimensional honeycomb lattice. Graphene acts as a semimetal because of its zero bandgap and linear energy dispersion close to the Dirac points, which makes it great for high-speed electronics but less appropriate for digital switching applications that need a finite bandgap [17]. Because of its stability and low contact resistance, graphene has been extensively investigated as an electrode material, charge transport layer, and sensing interface in memory and neuromorphic devices. Additionally, recent studies highlight the use of graphene in transparent and flexible electronics, where its atomic thinness allows for mechanical robustness and extreme device scalability [30].

3.1.2 Transition Metal Dichalcogenides (TMDs)

A wide class of two-dimensional materials known as transition metal dichalcogenides (TMDs) has the basic formula MX, , where M is a transition metal (such as Mo or W) and X is a chalcogen (such as S, Se, or Te). TMDs are very appealing for logic, optoelectronic, and memory applications because, in contrast to graphene, several of them have intrinsic bandgaps that change from indirect in bulk form to direct in monolayer thickness [1]. Low-power field-effect transistors and resistive switching devices are made possible by materials like MoS, and WS, , which have shown superior electrostatic control and decreased short-channel effects. Due to their strong light-matter interactions and low switching voltages, recent research emphasizes the combination of TMD-based memristors and memtransistors for in-memory computing [22].

3.1.3 MXenes

The A-layer of stacked MAX phases is selectively etched to produce transition-metal carbides, nitrides, or carbonitrides with the general formula Mn+1XnTx. MXenes are a relatively novel family of 2D materials. MXenes are very adaptable for electronic and energy-storage applications due to their metallic conductivity, hydrophilic surfaces, and adjustable surface terminations (-O, -OH, -F) [2]. Because of their high electrical conductivity and chemical stability, MXenes have drawn interest for their application in resistive switching layers and electrodes in memory systems. To enable dependable incorporation into next-generation non-volatile memory and neuromorphic computer systems, ongoing research focuses on increasing oxidation resistance and large-scale synthesis [21].

3.1.4 Black Phosphorus

A unique combination of high carrier mobility and a thickness-dependent direct bandgap spanning from ~0.3 eV (bulk) to ~2.0 eV (monolayer) is provided by black phosphorus (BP), a layered two-dimensional material made of phosphorus atoms organized in a puckered lattice structure. In electronic and optoelectronic applications, BP can bridge the gap between graphene and TMDs thanks to its configurable bandgap [32]. Because of its anisotropic transport characteristics, black phosphorus has demonstrated potential in memory technologies in resistive switching and charge-trapping devices. Its vulnerability to environmental deterioration is still a problem, though, which motivates continued research into surface passivation and encapsulation methods to improve long-term device durability [21].

3.1.5 Hexagonal Boron Nitride (h-BN)

A 2D insulator with a wide bandgap (~5.9 eV) and a crystal structure resembling graphene, hexagonal boron nitride (h-BN) is made up of alternating boron and nitrogen atoms. h-BN is frequently utilized as an insulating and dielectric layer in van der Waals heterostructures because of its exceptional thermal stability, chemical inertness, and atomically flat surface [33]. h-BN is essential in memory devices as a defect-engineered switching medium, charge-blocking layer, and tunneling barrier. According to recent studies, defect-controlled h-BN can display resistive switching behaviour, extending its function in non-volatile memory systems from passive insulation to active involvement [21].

3.2 Unique Electrical, Optical, and Mechanical Properties

Due to intense quantum confinement and reduced dimensionality, two-dimensional (2D) materials display a variety of electrical, optical, and mechanical properties that are essentially distinct from those of bulk materials. When downsized to nanoscale dimensions, many 2D materials exhibit superior electrostatic control, increased carrier mobility, and decreased short-channel effects. For instance, semiconducting 2D materials like transition metal dichalcogenides (TMDs) offer tunable band gaps that enable low-power switching behaviour crucial for memory and logic devices, while graphene displays exceptionally high carrier mobility exceeding 10æ% cm^2 V{ ^{1} s{ ^{1} [4, 30]. Furthermore, robust gate coupling is made possible by the atomically thin nature of 2D materials, which greatly reduces operating voltages and energy consumption in electrical and memory structures.

Even at monolayer thickness, 2D materials exhibit substantial light-matter interaction optically, resulting in increased absorption, photoluminescence, and excitonic effects. For example, monolayer TMDs have direct band gaps that provide effective light emission and detection, which makes them appropriate for photonic computing systems and optoelectronic memories [31]. Additionally, strain engineering, layer number modification, and heterostructure generation can be used to adjust the optical response of 2D materials, providing design flexibility not possible with bulk materials. As seen by graphene's high Young's modulus and fracture strength, 2D materials have remarkable mechanical strength and flexibility while yet being pliable and stretchable. The development of flexible, wearable, and mechanically robust memory systems is made possible by this special mechanical resilience, whereas typical bulk materials frequently fail because of brittleness and thickness limitations [34].

3.3 Advantages of 2D Materials over Bulk Materials

For next-generation electrical and memory systems, the use of 2D materials over traditional bulk materials offers a number of significant advantages. Ultimate thickness scaling is one of the biggest advantages since 2D materials can be reduced to a single atomic layer without losing their crystal structure. This allows for ultra-dense integration and ongoing device miniaturization beyond the capabilities of bulk silicon technologies [30]. This atomic-scale thickness reduces short-channel effects and leakage currents, two significant issues in bulk semiconductor devices that are being aggressively grown. Furthermore, the development of superior interfaces and van der Waals heterostructures is made possible by the lack of dangling bonds on the surfaces of 2D materials, which lowers interface trap densities and enhances device dependability [4].

The 2D material family's material diversity and tunability is another important benefit. 2D materials offer a broad range of electronic behaviours, from metallic (graphene, MXenes) to semiconducting (TMDs, black phosphorus) and insulating (h-BN), in contrast to bulk materials with set properties, allowing heterogeneous integration within a single device platform. This adaptability facilitates the construction of multifunctional devices, such as logic-in-memory and neuromorphic computing systems, which allow for the effective execution of several tasks within small structures [22]. Furthermore, low-temperature processing and back-end-of-line (BEOL) compatibility are made possible by 2D materials, which is essential for directly integrating memory components on top of already-existing CMOS circuitry. These benefits, along with their energy efficiency, radiation tolerance, and mechanical flexibility, make 2D materials excellent options for either supplementing or replacing bulk materials in upcoming high-performance and low-power memory technologies [1, 34].

4. Tunability in 2d Materials

2D materials offer remarkable tunability in their electrical, optical, and mechanical properties, enabling precise control for next-generation electronic, optoelectronic, and memory devices. The atomic-scale thickness and reduced dimensionality of 2D materials allow multiple strategies to modify their properties, including bandgap engineering, strain application, defect introduction, doping, and electrostatic or chemical gating. These tunable features are essential for designing high-performance and energy-efficient devices such as transistors, memristors and photodetectors.

4.1 Bandgap Engineering

In order to maximize device performance, bandgap engineering in 2D materials entails altering the electrical energy gap between the valence and conduction bands. To improve their optical absorption and photoluminescence for optoelectronic and memory applications, semiconducting TMDs like MoS, , for instance, show a transition from an indirect bandgap in bulk form to a direct bandgap in monolayers [1]. Additionally, bandgap can be adjusted by external variables such as chemical functionalization, heterostructure creation, or vertical electric fields, allowing for resistive switching layers in memory and low-power switching in FETs. devices [30].

4.2 Thickness and Layer-Dependent Properties

The physical and electrical properties of 2D materials are strongly influenced by the number of layers. For instance, optical sensitivity, carrier mobility, and switching behaviour are affected by the direct bandgap (~1.8 eV) of monolayer MoS, and the indirect bandgap (~1.2 eV) of bilayer or multilayer MoS, [4]. Layer-dependent characteristics also affect dielectric screening, mechanical flexibility, and thermal conductivity, giving designers a variety of options to maximize memory device performance and CMOS technology integration.

4.3 Strain Engineering

A flexible method for adjusting the characteristics of 2D materials without changing their chemical makeup is mechanical strain. Tensile or compressive strain can cause anisotropic electrical or optical behaviour, change carrier effective mass, and alter band structure [22]. Strain engineering is an essential method for flexible electronics and high-performance memory architectures since it has been demonstrated to increase photodetector responsivity, lower switching voltages in memory devices, and improve charge carrier mobility.

4.4 Defect and Vacancy Engineering

It is possible to purposefully create defects and vacancies in 2D materials to alter their optical, magnetic, and electrical characteristics. For instance, localized mid-gap states can be produced by carbon vacancies in graphene or sulfur vacancies in MoS, , improving resistive switching behaviour in ReRAM devices [21]. Controlled defect engineering offers design freedom for neuromorphic computers, memristive devices, and sensors by enabling customization of conductivity, trap states, and chemical reactivity.

4.5 Doping and Fictionalization

The carrier concentration and work function of 2D materials are frequently altered by chemical doping and surface fictionalization. For example, surface functional groups on MXenes or TMDs can change electrical and electrochemical properties, while nitrogen or boron doping in graphene can cause p-type or n-type behavior [21]. These techniques increase environmental stability, boost device performance and make integration into multifunctional electronics and hybrid memory systems easier.

4.6 Electrostatic and Chemical Gating

Without permanently altering the material, electrostatic and chemical gating offer external control over 2D material properties. In 2D semiconductors, electrostatic gating through top or back gates can adjust the bandgap, change the carrier density, and move the Fermi level [30]. Similar to this, chemical gating through ionic liquids or adsorbates can adjust conductivity reversibly, allowing for logic-in-memory capabilities, adaptive sensor applications, and non-volatile memory operation. These gating techniques are essential for flexible electronics and low-power, reconfigurable systems.

5. Design Principles of 2d Material-Based Memory Devices

Atomic-scale characteristics, tunability, and compatibility with current semiconductor technology must all be carefully taken into account when designing memory devices based on 2D materials. Innovative device architectures are made possible by the special electrical, optical, and mechanical properties of 2D materials; nevertheless, these benefits must be properly utilized to provide great scalability, low power consumption, and dependable switching.

5.1 Device Structures and Architectures

A variety of topologies are used in 2D material-based memory devices, such as heterostructure-based van der Waals stacks, planar field-effect transistors, and vertical resistive switching layers. To precisely control resistive states through atomic-layer thickness, ReRAM systems, for example, frequently employ a thin 2D material as the active switching layer sandwiched between conductive electrodes [22]. Similar to this, memtransistors and TMD-based transistors use monolayer or few-layer channels for effective gate control, which lowers leakage currents and permits low-voltage operation [30]. While maintaining compatibility with CMOS back-end-of-line (BEOL) processes, hybrid architectures that combine 2D materials with traditional dielectrics or other 2D layers improve functionality and enable logic-in-memory and neuromorphic device implementations.

5.2 Charge Transport and Switching Mechanisms

The electrical structure, defect states, and interface quality of the material all affect charge transport and switching in 2D memory devices. ON/OFF states in resistive switching devices are controlled by the creation and rupture of conductive filaments or the modulation of defect-mediated trap states, whereas switching behaviour in phase-change or ferroelectric 2D-based devices is dominated by ionic motion or polarization reversal [35]. 2D materials' ultra-thinness improves energy efficiency by lowering switching voltages and enhancing electric field control. Fast read/write operations are also made possible by vertical tunnelling through heterostructures and lateral transport over high-mobility channels, which are essential for high-speed memory applications.

5.3 Interface Engineering and Contact Optimization

Because high contact resistance or interface traps can reduce switching reliability and endurance, interfaces and contacts are crucial to the performance of 2D material-based memory. To reduce Schottky barriers and maximize carrier injection, methods such as work function engineering, interfacial layer insertion, and chemical functionalization are used [17]**.** Van der Waals interfaces reduce trap density and improve uniformity in resistive switching or ferroelectric switching operations in heterostructure devices by removing dangling bonds. Device stability, reproducibility, and compatibility with large-scale fabrication processes are guaranteed via effective interface engineering.

5.4 Scaling Effects and Device Miniaturization

High-density memory arrays require aggressive scaling and device downsizing, which are made possible by the atomic thickness of 2D materials. Due to fewer short-channel effects and low leakage currents, 2D materials, in contrast to bulk semiconductors, retain electronic performance at sub-10 nm dimensions [30]. Scaling also affects switching mechanisms. For instance, in transistor-based memory, monolayer TMD channels improve gate control while thinner resistive layers lower filament production voltages. To create dependable nanoscale devices, however, issues like edge flaws, ultra-thin layer heterogeneity, and quantum confinement effects must be carefully controlled through material synthesis, patterning, and process optimization.

6. Integration of Tunable 2d Materials In Memory Technologies

High-performance, low-power, and scalable devices are made possible by the incorporation of 2D materials into developing memory technologies. Their mechanical, optical, and electrical characteristics can be precisely adjusted to govern endurance, retention, and switching behaviour. Additionally, novel topologies like lateral memtransistors and vertical heterostructures, which increase device density and energy efficiency while permitting multifunctional memory applications, are made possible by 2D materials [Figure 2].

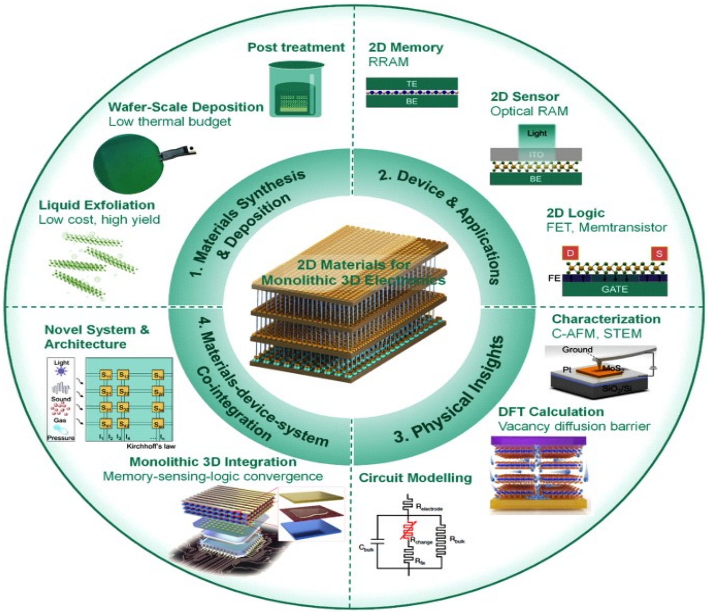

Figure 2: Integration of Tunable 2D Materials in Memory Technologies

Source: Zhang *et al.*, 2024; Zhou *et al.*, 2024

6.1 2D Materials in ReRAM Devices

Ion migration or defect-controlled conductive filaments are used to modulate resistance states in Resistive Random Access Memory (ReRAM). Because of their atomic-scale thickness, tunable defect density, and high conductivity, 2D materials including MoS, , graphene oxide, and MXenes have been employed as active layers or electrodes in ReRAM devices [21,22]. By precisely controlling filament generation and rupture, tunability via defect engineering, doping, or strain lowers switching voltages and increases endurance. High-density ReRAM arrays and multi-level resistive states can be made possible by layered heterostructures of TMDs or MXenes, which can further improve uniformity.

6.2 2D Materials in Phase Change Memory

Reversible transitions between amorphous and crystalline states are used by Phase Change Memory (PCM) to store data. Heat confinement is improved, programming currents are decreased, and switching speed is increased by using 2D materials like graphene, MoS, , or h-BN as electrodes, capping layers, or thermal buffers [30]. Van der Waals interactions also increase dependability at nanoscale dimensions and decrease interdiffusion. In 2D materials, strain or thickness tuning optimizes PCM performance for low-energy and high-speed memory operations by controlling thermal conductivity and electronic coupling.

6.3 2D Materials in Ferroelectric Memory

Ferroelectric layers' spontaneous polarization switching is essential to ferroelectric memory devices. CuInP, S„ and In, Se*f* are examples of 2D ferroelectrics that offer atomically thin, non-volatile polarization layers with low switching voltages and great endurance [31]. Strong non-volatile memory with extremely low power consumption is made possible by the programmable ferroelectric characteristics of these 2D materials, which can be designed by strain, layer number, or electrostatic gating. High-density ferroelectric memory arrays are supported by integration with 2D semiconductors, which enables effective charge injection and readout.

6.4 2D Materials in Neuromorphic and Synaptic Memory

The low-energy switching, multilevel conductance states, and analog tunability of 2D materials are advantageous for neuromorphic memory and artificial synapses. In memristive and memtransistor devices, MoS, , WS, , graphene oxide, and MXenes have been shown to mimic spike-timing-dependent plasticity and synaptic plasticity [22]. These materials' progressive conductance modulation made possible by defect engineering, doping, and electrostatic gating enables effective hardware for in-memory computer systems and artificial neural networks. Additionally, wearable and adaptable computing systems are supported by their adaptability and customizable reaction.

6.5 Heterostructures and Van der Waals Integration

Multifunctional memory devices with improved performance are made possible by the stacking of various 2D materials to create van der Waals heterostructures. For instance, merging graphene electrodes with h-BN insulating layers or TMD switching layers results in increased uniformity, lower contact resistance, and clean, defect-free interfaces in resistive or ferroelectric switching [4,30]. Additionally, band alignment optimization, tunnelling control, and multi-functional operation are made possible by heterostructure engineering, which enables hybrid devices that integrate logic, memory, and neuromorphic functionalities on a single platform.

7. **Performance Metrics and Comparative Analysis**

A thorough grasp of switching speed, power consumption, endurance, scalability, and reliability is necessary when evaluating 2D-material-based memory devices because these factors together define their applicability for next-generation memory applications. Because of their atomic-scale thickness, customizable electrical characteristics, and clean van der Waals interfaces, 2D materials have distinct benefits over conventional bulk-based memory systems.

7.1 Switching Speed

Defect density, layer thickness, and charge transport techniques all have a significant impact on switching speed in 2D-based memory devices. In comparison to many traditional flash memories, ReRAM and memristor systems employing 2D materials as MoS, and MXenes have shown switching times in the nanosecond to microsecond range [22]. Rapid ON/OFF transitions are made possible by the ultra-thin active layers, which also improve electric field control and shorten ion migration distances. Due to heat confinement in atomic-thin layers, phase-change memory devices using 2D materials also benefit from quick crystallization dynamics, allowing for high-speed read/write operations [30].

7.2 Power Consumption

Strong gate control, lower leakage currents, and lower switching voltages are some of the ways that 2D materials contribute to low-power operation. In comparison to traditional silicon or oxide-based memory, lower programming currents are possible in ReRAM and ferroelectric devices due to the atomic-scale thickness of channels and switching layers [1]. Furthermore, 2D semiconductors' electrostatic and chemical gating lowers the energy needed for charge modulation, making them appropriate for wearable and energy-efficient electronics.

7.3 Endurance and Retention

Important measures for memory dependability include endurance (the quantity of dependable switching cycles) and retention (the capacity to maintain memory state over time). Under ideal circumstances, 2D material-based memory have potential durability exceeding 10–10 cycles and retention periods of 10–10 seconds [21]. While ferroelectric 2D materials offer non-volatile polarization that preserves information without constant power, Van der Waals interfaces and defect-engineered layers increase stability by reducing interface traps and material degradation.

7.4 Scalability

Memory cells can achieve sub-10 nm dimensions without sacrificing performance because 2D materials' atomic thickness naturally facilitates aggressive device scaling [4]. Dense memory arrays appropriate for high-capacity applications are made possible by reduced short-channel effects, minimal leakage, and high carrier mobility. By assembling heterostructures layer by layer, vertical scaling is further improved, and three-dimensional memory integration is made possible without the difficulties caused by lattice mismatch that are common in bulk materials.

7.5 Reliability and Stability

Material quality, interface design, and environmental stability all affect how reliable and stable 2D-based memories are. Although 2D materials have strong van der Waals bonds and clean surfaces, issues including oxidation (in black phosphorus), moisture sensitivity, and defect variability need to be resolved [30]. Strategies for defect management, surface passivation and encapsulation have been effectively used to improve long-term operational stability, guaranteeing consistent switching behaviour and retention under a range of electrical and thermal pressures.

8. Fabrication Techniques and Challenges

Environmental Stability, Device Fabrication, Cmos Technology Integration, And Synthesis techniques all play a major role in the practical application of 2D materials in memory devices. Even though 2D materials have remarkable mechanical, optical, and electrical qualities, producing homogeneous, high-quality layers at scale is still quite difficult.

8.1 Synthesis of 2D Materials

8.1.1 Mechanical Exfoliation

Peeling tiny layers from bulk crystals is known as mechanical exfoliation, or the "Scotch tape method." This method is perfect for basic research and prototype devices since it yields high-quality, flawless monolayers [17]. However, its low reproducibility and poor scalability prevent it from being used in large-scale industrial applications.

8.1.2 Chemical Vapour Deposition (CVD)

Large-area 2D materials like graphene, MoS, , and WS, are frequently synthesized via CVD. CVD can provide homogeneous monolayers appropriate for wafer-scale device production by regulating temperature, pressure, and precursor flow [30]. Although CVD is scalable, it frequently introduces grain boundaries and necessitates careful transfer procedures to prevent contamination, which can affect the uniformity and performance of the device.

8.1.3 Solution-Based Methods

2D nanosheets distributed in solvents can be produced in large quantities using solution-based methods such as chemical synthesis and liquid-phase exfoliation. Flexible and wearable device applications are made possible by these techniques' compatibility with printing and coating processes [1]. Controlling layer thickness, flake size and producing defect-free films—all essential for dependable memory operation—present difficulties.

8.2 Device Fabrication and Patterning

It takes exact patterning, electrode deposition, and layer stacking to fabricate memory devices from 2D materials. To preserve alignment accuracy while preventing damage to ultra-thin layers, lithography and etching methods must be improved. Complex heterostructures for ReRAM, PCM, and ferroelectric devices are made possible by sophisticated techniques like van der Waals assembly and direct-write printing. Because even little flaws can cause unpredictability in switching behaviour and retention, maintaining clean interfaces and preventing contamination are essential [21].

8.3 Integration with CMOS Technology

For commercial deployment, 2D materials must be integrated with traditional CMOS platforms. Thermal budget restrictions are a problem since prefabricated circuits can be harmed by high-temperature development methods. Low-temperature CVD, transfer techniques, and back-end-of-line (BEOL) compatible deposition techniques are being developed to provide smooth integration without compromising device performance [30]. In hybrid 2D-CMOS memory designs, interface engineering is also essential for lowering contact resistance and guaranteeing dependable switching.

8.4 Stability and Environmental Issues

Device dependability is impacted by the environmental stability of 2D materials. Materials that are susceptible to moisture and oxygen, such as black phosphorus, can lose their electrical qualities [4]. To reduce oxidation and chemical reactions, passivation layers, controlled ambient processing, and encapsulation are required. Another issue is thermal stability, particularly in high-density or high-speed memory arrays where Joule heating can cause unwanted phase transitions or deteriorate thin 2D layers. For long-term device performance and commercialization, these stability issues must be resolved.

9. Recent Progress and Key Experimental Demonstrations

The extraordinary potential of 2D materials in next-generation memory devices has been brought to light by recent experimental investigations. Monolayer CuInP, S,, -based 2D ferroelectric memories demonstrated non-volatile operation with low switching voltages, while MoS, - and WS, -based ReRAM devices demonstrated fast switching times (<10 ns) and high endurance (>10æ% cycles) [1, 21] While heterostructures based on graphene and h-BN have shown enhanced contact performance and homogeneity across large arrays, MXene-based ReRAM devices have achieved multi-level resistive states, allowing better store density [21].

2D-material-based devices can surpass traditional flash memories in terms of switching speed, energy efficiency, and scalability potential, according to performance benchmarks from the literature. For instance, programming currents in ReRAM devices with 2D channels are in the microampere range, whereas silicon oxide-based devices have milliamperes. Ferroelectric 2D memories are also suitable for low-power and high-density applications, as evidenced by their capacity to maintain information for more than 10 seconds with no degradation under frequent switching [30]. Together, these investigations show that 2D materials can either achieve or surpass the critical performance parameters needed for next-generation non-volatile memory.

10. Challenges and Limitations

Despite remarkable experimental advancements, a number of obstacles prevent 2D-material-based memory systems from being widely used. Because irregular layer thickness, grain boundaries, and flaws can result in uneven switching and decreased device reliability, material homogeneity is still a crucial concern [17]. Another constraint is large-area fabrication; although methods like CVD allow wafer-scale growth, it is still difficult to regulate flaws, layer homogeneity, and reproducibility over vast regions [30].

Charge injection, undesired trap states, and switching performance can all be negatively impacted by interface flaws between 2D layers and electrodes or dielectrics. Maintaining device lifespan and retention requires achieving clean, flawless interfaces, particularly in heterostructures [21].

Despite remarkable experimental advancements, a number of obstacles prevent 2D-material-based memory systems from being widely used. Because irregular layer thickness, grain boundaries, and flaws can result in uneven switching and decreased device reliability, material homogeneity is still a crucial concern [17]. Another constraint is large-area fabrication; although methods like CVD allow

wafer-scale growth, it is still difficult to regulate flaws, layer homogeneity, and reproducibility over vast regions [30]. Charge injection, undesired trap states, and switching performance can all be negatively impacted by interface flaws between 2D layers and electrodes or dielectrics. Maintaining device lifespan and retention requires achieving clean, flawless interfaces, particularly in heterostructures [22].

11. Future Perspectives and Research Directions

Emerging AI-driven memory systems, where ultra-fast, energy-efficient, multilayer memory is crucial for in-memory computing and real-time data processing, are directly related to the future of 2D-material-based memory devices [22]. Devices can mimic synaptic behaviour by taking advantage of the programmable characteristics of 2D materials, allowing for neuromorphic designs that use less energy and latency than traditional von Neumann systems.

Another interesting avenue is the development of wearable and flexible memory devices. 2D materials like graphene and MXenes can be integrated into flexible substrates for wearable electronics and health monitoring systems due to their mechanical flexibility [1]. These devices can be used for continuous monitoring applications without sacrificing user comfort thanks to their low-power operation and ultrathin profiles.

Integration of 3D memory offers a chance to boost storage density even more. High-capacity, energy-efficient memory arrays can be made possible by stacking Van der Waals heterostructures vertically to create multi-layered systems without lattice-matching restrictions [4]. Lastly, the focus on low-power and sustainable electronics is in line with international energy efficiency objectives. 2D materials can help create eco-friendly electrical devices by lowering operating voltages, minimizing leakage, and enabling low-temperature production techniques.

12. Applications of 2d Material-Based Memory Architectures

Memory devices based on 2D materials have the potential to influence several application areas. Compared to traditional flash or DRAM devices, high-density data storage can store more data in smaller footprints thanks to atomic-scale thickness and multi-level resistive states [21]. Fast, low-power 2D-based memories in edge computing improve efficiency in distributed IoT systems by reducing latency through local processing. Similar to this, neuromorphic computing uses 2D materials' analogue tunability to simulate synaptic plasticity, allowing hardware acceleration for AI and machine learning applications [22]. Lastly, for real-time data gathering and processing, the Internet of Things (IoT) depends on small, versatile, and energy-efficient memory devices. These criteria are satisfied by 2D-material-based memories, which enable wearable sensors, smart devices, and networked systems that function dependably in the face of mechanical stress and changing environmental circumstances [1,21].

13. Conclusion

2D materials provide a unique platform for next-generation memory technologies due to their atomic-scale thickness and multifunctional properties. They overcome the limitations of conventional memory by enabling fast switching, low power consumption, and excellent endurance in ferroelectric memory, PCM, MRAM, and ReRAM. Recent experimental demonstrations show promise in multi-level resistive states and neuromorphic computing, and significant techniques like strain tuning and bandgap engineering enhance device capabilities. However, commercial utilization is challenging due to problems including material consistency and device unpredictability. It is crucial to make constant advancements in the synthesis and fabrication of devices. Future applications in Internet of Things devices and AI-driven memory systems highlight the importance of 2D materials in the advancement of electrical technologies, as long as manufacturing and stability issues are fixed.

Acknowledgements

I would like to express my sincere gratitude to Prof. K. Sesha Maheswaramma for her invaluable guidance, support, and encouragement throughout the preparation of this review paper. Her insightful suggestions, constructive feedback, and expertise in the field of 2D materials and memory devices were instrumental in shaping the structure and content of this work. I am also thankful for her patience and motivation, which greatly assisted me in completing this research endeavor.

Conflict of Interest Statement: None

References

1. Wang, Q. H., Kalantar-Zadeh, K., Kis, A., Coleman, J. N., & Strano, M. S. (2023). Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. *Nature Nanotechnology, 18*, 123–136. https://doi.org/10.1038/nnano.2023.11
2. Anasori, B., Lukatskaya, M. R., & Gogotsi, Y. (2023). 2D metal carbides and nitrides (MXenes) for energy storage and electronics. *Nature Reviews Materials, 8*, 395–415. https://doi.org/10.1038/s41578-022-00498-1
3. Savanur, R. G., & Shankara, C. (2022). Recent advances in SRAM, DRAM and flash memory architectures: A comprehensive review. *JETIR, 9*(11), 697–705.

4. Novoselov, K. S., Mishchenko, A., Carvalho, A., & Castro Neto, A. H. (2016). 2D materials and van der Waals heterostructures. *Science, 353*(6298), aac9439. https://doi.org/10.1126/science.aac9439
5. Chhowalla, M., Jena, D., & Zhang, H. (2016). Two-dimensional semiconductors for transistors. *Nature Reviews Materials, 1*(11), 16052. https://doi.org/10.1038/natrevmats.2016.52
6. Goswami, K., Mondal, H. K., Das, S., & Banerjee, D. S. (2022). VAR-DRAM: Variation-aware framework for efficient dynamic random access memory design. *arXiv*. https://arxiv.org/abs/2201.06853
7. Ma, J., Liu, H., Yang, N., Zou, J., Lin, S., et al. (2022). Circuit-level memory technologies and applications based on 2D materials. *Advanced Materials, 34*(48), e2202371. https://doi.org/10.1002/adma.202202371
8. Springmann, R. (2020). Resistive random access memory (RRAM): An overview of materials, switching mechanism, performance, multilevel cell storage, modeling, and applications. *Nanoscale Research Letters, 15*, 90. https://doi.org/10.1186/s11671-020-03299-9
9. Wong, H. S. P., Lee, H. Y., Yu, S., Chen, Y. S., Wu, Y., Chen, P. S., Lee, B., Chen, F. T., & Tsai, M. J. (2012). Metal–oxide RRAM. *Proceedings of the IEEE, 100*(6), 1951–1970. https://doi.org/10.1109/JPROC.2012.2190369
10. Ma, Z. (2025). *Traditional and emerging memory technologies: Principles, applications and future trends*. Atlantis Press.
11. Xiong, X., Tong, A., Wang, X., Liu, S., Li, X., et al. (2021). Demonstration of vertically stacked CVD monolayer channels: MoS, nanosheets GAA-FET with Ion >700 µA/µm and MoS, /WSe, CFET. In *2021, IEEE International Electron Devices Meeting (IEDM)* (pp. 7.5.1–7.5.4). IEEE.
12. Kshirsagar, C. U., Xu, W., Su, Y., Robbins, M. C., Kim, C. H., et al. (2016). Dynamic memory cells using MoS, field-effect transistors demonstrating femtoampere leakage currents. *ACS Nano, 10*(9), 8457–8464. https://doi.org/10.1021/acsnano.6b03440
13. Kim, S., Park, J., & Lee, H. (2024). Defect-engineered hexagonal boron nitride for resistive switching memory applications. *Advanced Functional Materials, 34*(7), 2308124. https://doi.org/10.1002/adfm.202308124
14. Khosla, R., & Sharma, S. K. (2021). Integration of ferroelectric materials: An ultimate solution for next-generation computing and storage devices. *ACS Applied Electronic Materials, 3*(7), 2862–2897. https://doi.org/10.1021/acsaelm.0c00851

15. Hua, E., Spyrou, T., Ahmadi, M., Syed, A. M., Xun, H., Braic, L., van der Veer, E., Elatab, N., Gaydadjiev, G., & Hamdioui, S. (2025). PdNeuRAM: Forming-free, multi-bit Pd/HfO, ReRAM for energy-efficient computing. *arXiv*.
16. Wang, X., Chen, Y., Wu, G., Li, D., Tu, L., et al. (2017). Two-dimensional negative capacitance transistor with polyvinylidene fluoride-based ferroelectric polymer gating. *npj 2D Materials and Applications, 1*, 38. https://doi.org/10.1038/s41699-017-0040-4
17. Novoselov, K. S., Mishchenko, A., Carvalho, A., & Castro Neto, A. H. (2024). 2D materials and van der Waals heterostructures. *Science, 384*(6699), eadk1234. https://doi.org/10.1126/science.adk1234
18. Pang, C. S., Thakuria, N., Gupta, S. K., & Chen, Z. (2018). First demonstration of WSe, -based CMOS-SRAM. In *2018, IEEE International Electron Devices Meeting (IEDM)* (pp. 22.2.1–22.2.4). IEEE.
19. Wang, Y., Tang, H., Xie, Y., Chen, X., Ma, S., et al. (2021). An in-memory computing architecture based on two-dimensional semiconductors for multiply-accumulate operations. *Nature Communications, 12*(1), 3347. https://doi.org/10.1038/s41467-021-23719-3
20. Raoof, M., & Gholipour, M. (2025). Transition metal dichalcogenide FET-based dynamic random-access memory. *International Journal of Circuit Theory and Applications, 53*(3), 1764–1774. https://doi.org/10.1002/cta.4173
21. Zhou, H., Li, S., Ang, K.-W., & Zhang, Y.-W. (2024). Recent advances in in-memory computing using 2D materials. *Nano-Micro Letters, 16*, 135. https://doi.org/10.1007/s40820-024-01335-2
22. Luo, Z.-D., Yang, M.-M., Liu, Y., & Alexe, M. (2021). Emerging opportunities for 2D semiconductor/ferroelectric transistor-structure devices. *Advanced Materials, 33*(12), e2005620. https://doi.org/10.1002/adma.202005620
23. Xia, Y., Zong, L., Pan, Y., Chen, X., Zhou, L., et al. (2022). Wafer-scale demonstration of MBC-FET and C-FET arrays based on two-dimensional semiconductors. *Small, 18*(20), 2107650. https://doi.org/10.1002/smll.202107650
24. Zhang, X., Zhao, Y., & Gogotsi, Y. (2024). MXenes for advanced electronic and memory devices. *Advanced Electronic Materials, 10*(2), 2300678. https://doi.org/10.1002/aelm.202300678

25. Sebastian, A., Le Gallo, M., & Burr, G. W. (2018). Neuromorphic computing with non-volatile memory. *Nature Nanotechnology, 13*(6), 465–475. https://doi.org/10.1038/s41565-018-0189-z
26. McGuire, F. A., Lin, Y.-C., Price, K., Rayner, G. B., Khandelwal, S., et al. (2017). Sustained sub-60 mV/decade switching via the negative capacitance effect in MoS, transistors. *Nano Letters, 17*(8), 4801–4806. https://doi.org/10.1021/acs.nanolett.7b01584
27. Biswas, R., Duan, J., Deng, S., Niu, X., Qin, Y., Panigrahi, P., Parekh, V., Joshi, R., Ni, K., & Narayanan, V. (2025). Single-cell universal logic-in-memory using 2T-nC FeRAM. *arXiv*.
28. Ferdaus, F. (2022). *Facilitating emerging non-volatile memories for ensuring security and device trust* (Doctoral dissertation, Florida International University).
29. Jacob, B. (2002). *DRAM systems research: Architectures, interfaces, and systems*. University of Maryland.
30. Liu, A., Zhang, X., Liu, Z., Li, Y., Peng, X., & Li, X. (2024). The roadmap of 2D materials and devices toward chips. *Nano-Micro Letters, 16*, 121. https://doi.org/10.1007/s40820-023-01273-5
31. Si, M., Su, C., Jiang, C., Conrad, N. J., Zhou, H., et al. (2017). Steep slope MoS, 2D transistors: Negative capacitance and negative differential resistance. *arXiv*.
32. Li, L., Yu, Y., Ye, G. J., Ge, Q., Ou, X., Wu, H., Feng, D., Chen, X. H., & Zhang, Y. (2023). Black phosphorus field-effect transistors. *Nature Nanotechnology, 18*, 372–377. https://doi.org/10.1038/nnano.2023.45
33. Dean, C. R., Young, A. F., Meric, I., Lee, C., Wang, L., Sorgenfrei, S., et al. (2023). Boron nitride substrates for high-quality graphene electronics. *Nature Nanotechnology, 18*, 107–113. https://doi.org/10.1038/s41565-022-01259-6
34. Lee, C., Wei, X., Kysar, J. W., & Hone, J. (2023). Measurement of the elastic properties and intrinsic strength of monolayer graphene. *Science, 385*(6712), 1038–1042. https://doi.org/10.1126/science.1210893
35. Wang, C., You, L., Cobden, D., & Wang, J. (2023). Towards two-dimensional van der Waals ferroelectrics. *Nature Materials, 22*(5), 542–552. https://doi.org/10.1038/s41563-022-01422-y