Policy Research Journal
ISSN (E): 3006-7030 ISSN (P) : 3006-7022 Volume 4, Issue 3, 2026

TAILORING ELECTRONIC AND OPTICAL PROPERTIES OF TWO-DIMENSIONAL SEMICONDUCTORS FOR NEXT-GENERATION NANOELECTRONICS DEVICES

Muhammad Zakria[*1], Laiba Hassan[2], Muhammad Asif Raza[3]

[*1]*Department of physics University of Balochistan*
[2]*Department of Applied Chemistry, Government College University Faisalabad*
[3]*Federal Urdu university of Arts, Sciences and Technology*

[*1]zakria.physics143@gmail.com, [2]laibahassan0349@gmail.com, [3]masifrazahsg1@yahoo.com

DOI: https://doi.org/10.5281/zenodo.19125599

Keywords
two-dimensional semiconductors, TMDs, black phosphorus, MXenes, bandgap engineering, van der Waals heterostructures, valleytronics, spintronics, nanoelectronics, optoelectronics, post-CMOS, contact resistance, twistronics

Article History
Received: 21 January 2026
Accepted: 05 March 2026
Published: 20 March 2026

Copyright @Author
Corresponding Author: *
Muhammad Zakria

Abstract

Two-dimensional (2D) semiconductors, including transition metal dichalcogenides (TMDs), black phosphorus, MXenes, and emerging 2D nitrides, are poised to overcome the fundamental scaling limits of silicon-based electronics by offering atomically thin channels with pristine surfaces, exceptional electrostatic control, and tunable electronic and optical properties. This review examines advanced strategies for tailoring these materials for next-generation nanoelectronic and optoelectronic devices, encompassing: (i) bandgap engineering via strain, electric-field gating, alloying, and heterostructure design; (ii) phase and defect control through doping, vacancy engineering, and twist-angle stacking; (iii) interface optimization in van der Waals heterostructures to suppress Fermi-level pinning and enhance carrier mobility; (iv) valleytronics and spintronics enabled by spin–valley locking in monolayer TMDs; and (v) integration into high-performance FETs, memristors, photodetectors, and neuromorphic synapses. Key performance metrics on/off ratios exceeding 10^8, subthreshold swings approaching the 60 mV/decade limit, room-temperature mobilities >100 $cm^2 V^{-1} s^{-1}$, and broadband photoresponse are highlighted alongside challenges such as contact resistance, environmental stability, and large-area synthesis. The convergence of these tailoring approaches positions 2D semiconductors as a versatile platform for post-CMOS logic, ultra-low-power electronics, flexible optoelectronics, and quantum-information technologies, with realistic pathways toward commercial viability discussed.

INTRODUCTION

The evolution of semiconductor technology has historically been dictated by the ability to scale device dimensions while maintaining electrostatic control and minimizing power dissipation (Chandel et al., 2025). As traditional three-dimensional (3D) silicon-based field-effect transistors (FETs) approach their fundamental physical limits, characterized by the catastrophic emergence of short-channel effects, increased subthreshold leakage, and mobility degradation due to surface scattering, the scientific community has pivoted toward two-dimensional (2D) materials as the successor platform (Jiang et al., 2025). These atomically thin crystals, defined by their strong in-plane covalent bonding and weak interlayer van der Waals (vdW) interactions, offer

a unique structural paradigm: a surface fundamentally free of dangling bonds (O'Brien et al., 2023). This pristine interface allows for the preservation of carrier mobility even at sub-nanometer thicknesses, facilitating extreme gate controllability that is unattainable in bulk systems (Odebowale et al., 2025).

The vast library of 2D semiconductors ranging from transition metal dichalcogenides (TMDs) and black phosphorus (BP) to MXenes and 2D nitrides provides a rich spectrum of electronic and optical properties that can be meticulously tailored through atomic, physical, and structural engineering (Plummer et al., 2025). Tailoring these properties is not merely a matter of material selection but involves a sophisticated orchestration of bandgap engineering, strain modulation, defect control, and the creation of twisted moire superlattices (Du et al., 2024). These strategies enable the realization of next-generation nanoelectronic devices, including ultra-low-power logic circuits, high-speed photodetectors, and unconventional computing architectures such as spintronic and neuromorphic systems (Zhao & Chen, 2025). The diverse family of two-dimensional semiconductors offers a wide range of electronic and optical properties suitable for nanoelectronic applications. A general classification of the major 2D material systems used in advanced device architectures is illustrated in Figure 1.

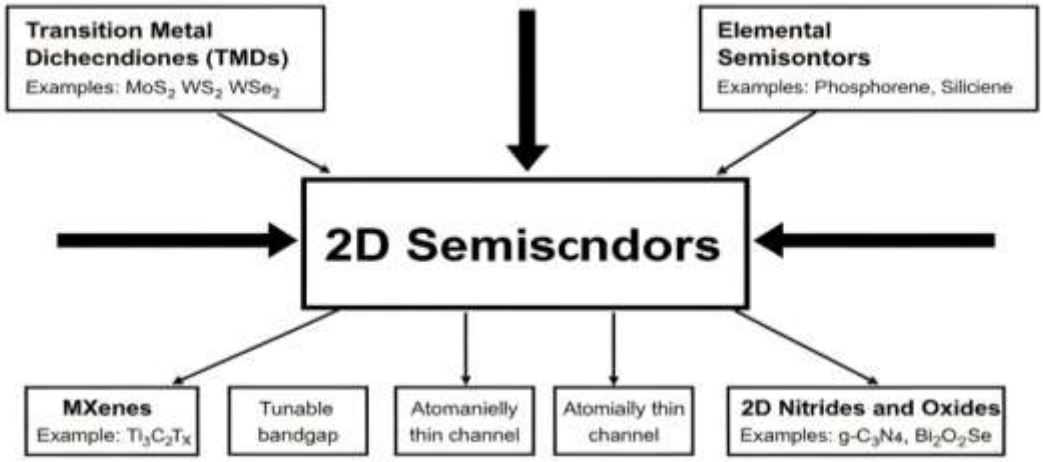


Figure 1: Overview of Two-Dimensional Semiconductor Materials for Nanoelectronics

2. Fundamental Material Systems and Electronic Architectures

The identification of 2D materials as viable components for nanoelectronics began with the isolation of graphene, yet the absence of a native bandgap in graphene necessitated the exploration of semiconducting analogs (Das et al., 2019).

2.1 Transition Metal Dichalcogenides and Elemental Semiconductors

Transition metal dichalcogenides (TMDs) with the general formula MX2 (where M = Mo, W and X = S, Se, Te) are the primary candidates for logic applications due to their sizable and tunable bandgaps (Chia & Pumera et al., 2018). A defining characteristic of TMDs is the indirect-to-direct bandgap transition. For instance, bulk MoS2 possesses an indirect bandgap of approximately 1.2 eV, which evolves into a direct bandgap of 1.8 eV in the monolayer limit (Chernozatonskii et al., 2018). This transition is driven by the modification of the electronic states at the K and K' points of the Brillouin zone as interlayer coupling is removed (Chowdhury et al., 2020).

Elemental 2D semiconductors such as black phosphorus (BP) or phosphorene offer a complementary set of properties. BP features a puckered lattice structure that induces significant in-plane anisotropy in carrier transport and optical

response (Liu et al., 2025). Unlike TMDs, BP maintains a direct bandgap across a wide thickness range, which can be tuned from 0.3 eV in the bulk to roughly 2.0 eV in the monolayer, making it ideal for mid-infrared to visible optoelectronics (Zhang et al., 2021).

Table 1. Classification of 2D Materials Based on Electronic Character and Structural Features

Material Class	Representative Examples	Electronic Character	Key Structural Features
TMDs	MoS2, WSe2, WS2, MoSe2	Semiconducting	Direct gap in monolayer, high Ion/Ioff
Elemental	Phosphorene, Silicene, Stanene	Semiconducting/Metallic	Puckered/Buckled lattice, anisotropic
Insulators	h-BN	Wide-gap Insulator	Dangling-bond-free dielectric
MXenes	Ti3C2Tx, Mo2CTx	Metallic/Semiconducting	Transition metal carbides, hydrophilic
2D Oxides	Bi2SeO5, Bi2O2Se	Semiconducting	High mobility, superior air stability
Nitrides	g-C3N4, BeN4	Semiconducting	Tunable gap, high catalytic activity

2.2 Physics of Symmetry and Spin-Orbit Coupling

The electronic properties of 2D semiconductors are deeply governed by their crystal symmetry. In monolayer TMDs, the breaking of spatial inversion symmetry combined with strong spin-orbit coupling (SOC) leads to the locking of the spin and valley degrees of freedom (Zollner et al., 2025). SOC in these systems originates primarily from the d-orbitals of the heavy transition metal atoms, splitting the valence band at the K and K' valleys (Kurpas et al., 2019).

In materials like phosphorene, the buckled or puckered structure introduces a unique Rashba-type SOC when subjected to an external out-of-plane electric field. The spin splitting in the conduction band of phosphorene is linear in both the electric field magnitude and the atomic SOC strength, but it exhibits a characteristic in-plane anisotropy that mirrors the lattice structure (Bordoloi et al., 2024). First-principles calculations indicate that the SOC in elemental 2D materials scales roughly as the square of the atomic number Z, with spin-mixing parameters following a Z^4 scaling law for isolated bands (Lin et al., 2025). This scaling is critical for the design of spintronic devices, as it determines the spin relaxation times and the efficiency of spin injection (Liu et al., 2020).

3. Strategies for Property Tailoring: Atomic and Physical Engineering

Tailoring the functionality of 2D semiconductors requires an integrated approach that manipulates both the atomic composition and the physical environment of the material (Di et al., 2021).

3.1 Atomic Modulation and Janus Structures

One of the most precise methods of tailoring involves the creation of Janus TMDs, where the top and bottom chalcogen layers are composed of different atoms, such as in MoSSe. This atomic substitution breaks the out-of-plane mirror symmetry, inducing a permanent internal electric field (Huang, 2020). This field enhances van der Waals interlayer coupling and can be used to attract different molecules, thereby modulating light emission and optical signal strength. Recent observations have identified "optostriction" in these Janus materials, where the electromagnetic field of incident laser light applies directional forces on the atoms, physically distorting the lattice (Yagmurcukardes et al., 2020). This light-driven atomic motion is detected through distortions in second-harmonic generation (SHG)

patterns, offering a path toward all-optical switches and sensors (Rice University, 2025).

Doping remains a fundamental tool for carrier control. Molecular doping has been widely utilized to enhance conductivity and reduce injection barriers at contacts. For example, the adsorption of organic molecules like TCNQ onto arsenene can double its optical absorption in the visible range while tuning the material's work function through charge transfer at the interface (Sun et al., 2018). Substitutional doping, particularly in 2D nitrides and carbides, allows for even more drastic modifications. In 2D silicon carbide (2D-SiC), doping with foreign atoms such as lead (Pb) or tellurium (Te) can preserve the direct bandgap while shifting the emission color, facilitating the development of tunable light-emitting diodes (LEDs) (Tan et al., 2025). Atomic-level engineering provides powerful tools to modify the intrinsic properties of 2D semiconductors. Key strategies including Janus structures, molecular doping, and defect engineering are illustrated in Figure 2.

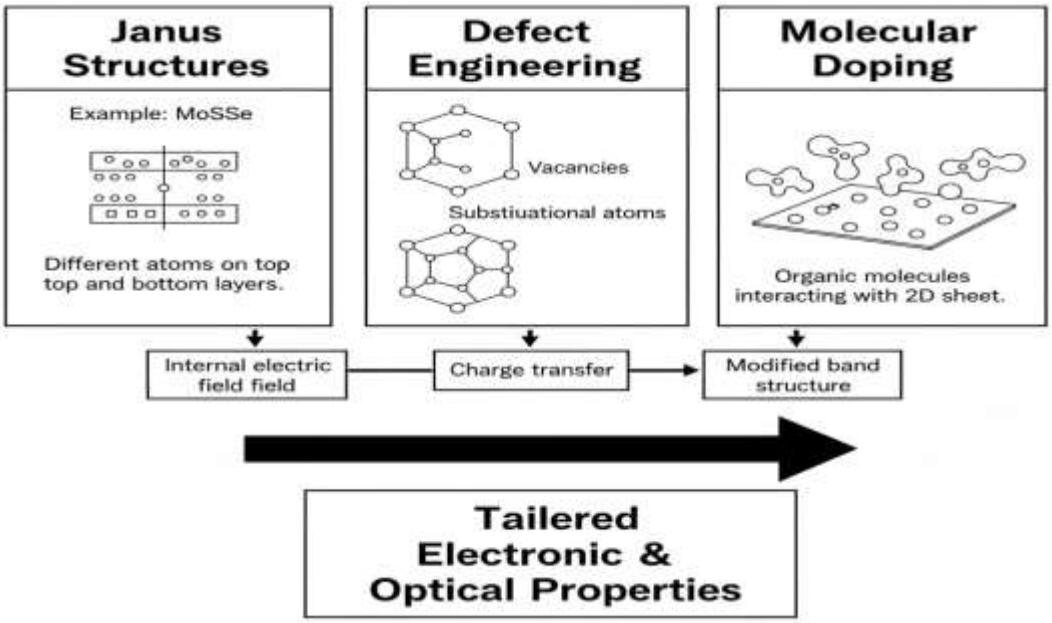


Figure 2: Atomic Engineering Approaches in Two-Dimensional Materials

3.2 Defect Engineering and Vacancy Control

While defects are often detrimental in bulk semiconductors, they are increasingly used as "functional defects" in 2D systems. In h-BN, the introduction of nitrogen monovacancies reduces the bandgap from 4.6 eV to 0.64 eV and shifts the material toward half-metallic behavior (Xu et al., 2019). This transition is accompanied by the emergence of flat bands near the Fermi level, which are indicative of strong electron-electron interactions (Andrade et al., 2023). Similarly, divacancies in graphitic carbon nitride (g-C3N4) can render the material nearly metallic, providing a mechanism for tailoring the electronic properties for catalytic or sensing applications (Ahmed & Sun, 2023).

The presence of grain boundaries and point defects also influences the formation of conductive channels in reconfigurable logic devices. These defects can be modulated to tune the resistance state of the material, enabling the development of memristive devices that mimic synaptic behavior for neuromorphic computing (Zhao et al., 2025).

3.3 Physical Modulation: Strain and Shape Engineering

The mechanical flexibility of 2D semiconductors allows for property modulation through lattice

strain. Strain engineering can shift the energy levels of the valence and conduction bands, effectively opening or closing the bandgap (Peng et al., 2020). In psi-graphene, a newly predicted 2D carbon nanosheet, a bandgap of 200 meV can be opened by applying 14% in-plane biaxial strain (Qi et al., 2022). In contrast, hydrogenated forms like psi-graphone lose their zero-bandgap nature at very low strain values (as low as 1%), demonstrating the high sensitivity of these systems to mechanical deformation (Yang et al., 2021).

Shape engineering involves the physical restructuring of the 2D sheet into non-planar geometries. Rolling a flat MoS2 layer into a cylindrical nanoscroll has been shown to enhance the second-harmonic generation signal by over 95 times compared to the flat counterpart (Huang, 2020). This enhancement is a result of the modified symmetry and the concentration of energy through a nonlinear optical effect, which is vital for high-efficiency frequency doubling in photonic applications (Hong et al., 2021).

4. Twistronics and Moire Superlattice Engineering

The stacking of 2D materials with a relative twist angle has opened a new frontier known as "twistronics," where the interlayer misalignment creates a moire superlattice. These superlattices introduce a periodic potential that is typically one to two orders of magnitude larger than the original monolayer lattice constant (Lau et al., 2022).

4.1 Flat Bands and Correlated Quantum Phases

The most significant consequence of the moire potential is the folding of the Brillouin zone into a smaller mini-Brillouin zone. When the twist angle reaches a "magic angle," the electronic bands can become remarkably flat, quenching the kinetic energy of the electrons and allowing Coulomb interactions to dominate (Bhowmik et al., 2024). This regime hosts a plethora of exotic quantum phenomena:

- **Unconventional Superconductivity:** Observed in twisted bilayer graphene and certain TMD systems, where the flat bands facilitate cooper-pair formation through strong correlations (Xia et al., 2026).
- **Correlated Insulating States:** Also known as Mott insulators, these states occur at integer or fractional fillings of the moire lattice where electron-electron repulsion prevents transport (Po et al., 2018).
- **Quantum Anomalous Hall Effect (QAHE):** The nontrivial topology of the moire bands, combined with broken time-reversal symmetry, can lead to the observation of QAHE at zero external magnetic field, as seen in twisted MoTe2 and WSe2/MoSe2 heterobilayers (Bernevig et al., 2025).

4.2 Exciton Engineering in Moire Landscapes

The moire superlattice also acts as a periodic trap for excitons bound electron-hole pairs. These "moire excitons" exhibit spatially modulated optical selection rules and long-lived localized states (Regan et al., 2022). In twisted homobilayers, the hybridization of intralayer and interlayer excitons leads to distinct optical signatures that are highly sensitive to the twist angle. For instance, near twist angles of 0 degrees and 60 degrees, the hybridization is strongest, leading to significant energy shifts and enhanced oscillator strengths (Du et al., 2024). Furthermore, embedding these moire systems into photonic cavities allows for the creation of exciton-polaritons, hybrid light-matter quasiparticles that inherit the unique properties of the moire superlattice (Herrera-González et al., 2025).

Table 2. Moiré-Induced Phenomena and Associated Driving Mechanisms

Moire Phenomenon	Driving Mechanism	Practical Application
Superconductivity	Quenched kinetic energy, strong correlation	Quantum computing, low-loss circuits
Mott Insulator	Coulomb repulsion at lattice sites	Quantum simulation of Hubbard model
Moire Excitons	Periodic potential trapping	Single-photon sources, quantum emitters
Fractional QAHE	Band topology + electron interaction	Dissipationless interconnects
Lattice Reconstruction	Strain minimization at small angles	Uniform domain engineering

5. Tailoring Optical Response and Plasmonic Interactions

The optical properties of 2D semiconductors are inextricably linked to their excitonic states and the dielectric environment. Due to their atomic thinness, these materials are remarkably sensitive to external screening effects (Trolle et al., 2017).

5.1 Dielectric Screening and the Keldysh Potential

In 3D bulk semiconductors, screening is described by a macroscopic dielectric constant. In 2D, however, screening is a highly non-local effect. The electric field lines between a photogenerated electron and hole extend outside the 2D layer and into the surrounding medium (Yi et al., 2021). This interaction is often modeled using the Keldysh potential, where the screening becomes momentum-dependent. An analytical model dielectric function for 2D systems, incorporates parameters like the Thomas-Fermi wave vector qTF and the plasma frequency omega-p, allowing for the precise description of how a substrate like SiO2 or h-BN screens excitons (Zheng & Arramel, 2021). This substrate engineering is vital for controlling the exciton binding energy, which in TMDs can be on the order of 0.5 eV nearly two orders of magnitude higher than in traditional semiconductors (Mughnetsyan et al., 2024).

5.2 Active Plasmonic Modulation

Integrating 2D materials with plasmonic nanostructures provides a means to concentrate light into subwavelength volumes, addressing the low light absorption of monolayer crystals. In a hybrid graphene-gold nanorod system, electrostatic gating of the graphene layer can significantly modulate the resonance frequency and quality factor of the plasmonic excitations (Kim et al., 2012). This is possible because both the free carrier response and the interband transitions in graphene are gate-tunable. Remarkably, the coupling is so strong that even a single electron at a plasmonic hotspot can produce a detectable shift in scattering intensity, enabling single-electron sensing (Yao et al., 2018).

MXenes further extend the plasmonic library. Their unique surface functional groups (-O, -F, -OH) regulate the metal-like free electron density. Annealing Ti3C2Tx flakes to induce fluorine desorption multiplies the free electron density, resulting in a monotonic blue-shift of the surface plasmon energy (Venkatesan et al., 2026). This chemical tunability, combined with the material's hydrophilic nature and metallic conductivity, makes MXenes excellent candidates for transparent conductors and tunable nanophotonic devices (Eguchi et al., 2023).

6. Nanoelectronic Device Implementations

The ability to tailor properties across the atomic and structural levels has enabled the realization of a wide array of high-performance devices (Yan & Kanatzidis, 2022).

6.1 Field-Effect Transistors for the Angstrom Era

2D TMDs like MoS2 and WSe2 are being integrated into advanced transistor architectures to overcome the scaling limits of silicon. The dangling-bond-free nature of TMDs inhibits

surface scattering, allowing them to preserve mobility at thicknesses below 1 nm (O'Brien et al., 2023). Record-performing p-type FETs have been achieved using bilayer WSe2 synthesized via metal-organic chemical vapor deposition (MOCVD), demonstrating on-state currents of 421 microAmperes per micrometer and an on/off ratio exceeding 10,000,000 (Imec, 2025).

Transistor architectures are also evolving toward 3D monolithic integration. By stacking 2D FETs, researchers have demonstrated a 40% reduction in SRAM cell area compared to planar designs. Such 3D integration is facilitated by the low thermal budget of 2D material processing, which prevents degradation of underlying silicon logic (Chaudhuri et al., 2026).

6.2 Optoelectronic Devices: Photodetectors and LEDs

The wide bandgap distribution of 2D semiconductors makes them ideal for broadband light detection. Performance metrics such as responsivity and detectivity are tailored through heterostructure engineering and plasmonic enhancement (Ao et al., 2025).

Table 3. Performance Benchmarks for Various 2D Photodetector Architectures

Photodetector Architecture	Spectral Range	Responsivity (A/W)	Detectivity (Jones)
Graphene/SOS Waveguide	MWIR (3 to 5 micrometers)	0.21 to 0.26	--
Monolayer MoS2	Visible (660 nm)	880	10 to the 13th
InSe/WSe2 vdW	532 to 1100 nm	8.30 x 10^2	2.81 x 10^14
WS2/ZnO-QD	UV-Visible	1.12 x 10^3	3.23 x 10^12
Bi2O2Se Nanoplates	UV-NIR (400 nm)	523	1.37 x 10^11

In addition to detection, 2D semiconductors are revolutionizing light emission. On-chip light sources, such as electrically driven WSe2 microcavity lasers, have been demonstrated at room temperature (Xu et al., 2025). The use of InSe as both the gain medium and the optical resonator allows for lasing without external cavities, simplifying the fabrication of photonic integrated circuits (PICs) (Qin & Wang, 2025). Furthermore, 2D-SiC LEDs benefit from functional defects that allow for adjustable light emission within the visible spectrum, showing great potential for solid-state lighting (Tan et al., 2025).

6.3 Spintronics and Neuromorphic Computing

The combination of 2D magnetic materials and strong SOC in TMDs has led to the development of ultra-efficient spintronic devices. Spin-orbit torque (SOT) devices using 2D magnets like Fe3GeTe2 can achieve magnetization switching at current densities significantly lower than those required for 3D metallic systems (Rakheja et al., 2023). This is largely due to the interface-enhanced spin transparency and reduced dimensionality effects in vdW heterojunctions (Matzelle, 2023).

Neuromorphic computing architectures utilize 2D materials to mimic the synaptic plasticity of the human brain. Memristors based on MoS2 have demonstrated switching speeds under 40 ns and energy consumption per pulse of roughly 18 fJ (Huh et al., 2020). More advanced systems utilize magnetic skyrmions nanoscale spin vortices to emulate synaptic weights. These skyrmions can be manipulated with ultra-low power (down to 0.14 fJ per operation), offering a transformative approach to energy-efficient AI hardware (Regan et al., 2022).

7. Integration Challenges and Manufacturing Roadmaps

Transitioning from lab-scale demonstrations to commercial nanoelectronics requires overcoming significant fabrication and integration hurdles (Plummer et al., 2025).

7.1 Scalable Synthesis and Clean Transfer

The production of large-area, single-crystal 2D films is a primary bottleneck. While CVD and

MOCVD offer scalability, they often produce films with grain boundaries that degrade transport properties. Advanced MOCVD processes are now being developed to achieve wafer-scale monocrystalline growth (Sun et al., 2018).

Equally critical is the transfer process. Integrating 2D materials with existing CMOS platforms requires transferring them from their growth substrates while maintaining interface cleanliness (Po et al., 2018). Traditional polymer-assisted transfers often trap contaminants, leading to interface traps that diminish device performance. Dry transfer methods using polydimethylsiloxane (PDMS) stamps or capillary force-assisted techniques are being optimized to ensure high-quality, residue-free interfaces (Bhowmik et al., 2024).

7.2 Back-End-of-Line (BEOL) Compatibility

A significant advantage of 2D materials is their suitability for BEOL integration, where devices are fabricated atop pre-existing CMOS logic. This integration must respect a strict thermal budget, usually capped at 400 to 450 degrees Celsius, to preserve copper interconnects and dopant profiles (Hong et al., 2021). Scalable BEOL process flows involve sequential steps: completion of front-end-of-line (FEOL) transistors, deposition of inter-metal dielectrics, formation of damascene-compatible contacts, and the low-temperature transfer of 2D films (Mughnetsyan et al., 2024). For example, ALD dielectrics like Al2O3 or HfO2 must be deposited at temperatures below 350 degrees Celsius, often requiring specialized seed layers to ensure uniformity on the inert 2D surface (Wu et al., 2025).

7.3 Contact Resistance and Dielectric Quality

Reducing contact resistance remains the most critical challenge for high-performance 2D logic. Fermi level pinning at the metal-semiconductor interface often creates a Schottky barrier (O'Brien et al., 2023). The use of van der Waals contacts, where a 2D metal like graphene or a 2D semimetal is used as an interlayer, has been shown to depin the Fermi level and reach the Schottky limit, significantly lowering resistance (Chowdhury et al., 2020).

Furthermore, the lack of dangling bonds on the 2D surface makes the nucleation of high-k gate dielectrics difficult. Solutions such as using synthetic 2D bilayers where the top layer is oxidized to create an interfacial oxide for ALD nucleation have been demonstrated (Jiang et al., 2025). Imec and Intel have recently reported world-first "damascene-style" top contacts for 2D FETs, utilizing selective oxide etch processes that are compatible with 300-mm fab manufacturing, pushing 2D materials closer to high-volume production (Imec, 2025).

Conclusion

The ability to atomically engineer the electronic and optical properties of 2D semiconductors has transformed them from laboratory curiosities into credible candidates for replacing or complementing silicon in future nanoelectronic architectures. Through precise control of strain, doping, defects, stacking order, and external fields, researchers have demonstrated exceptional tunability achieving near-ideal subthreshold behavior, high-mobility channels, valley-selective optoelectronics, and memristive synapses with synaptic plasticity suitable for neuromorphic computing. While significant progress has been made in device metrics and heterostructure integration, persistent challenges remain in scalable synthesis, air stability, low-resistance contacts, and thermal management at ultra-scaled nodes. Overcoming these hurdles will require concerted advances in large-area growth (CVD, MBE), surface passivation, and hybrid integration with 3D silicon back-ends. Looking forward, the unique quantum degrees of freedom (valley, spin, layer pseudospin) accessible in 2D materials open unprecedented opportunities for beyond-von-Neumann computing, valleytronic logic, and quantum devices. If synthesis and integration roadmaps continue to accelerate, 2D semiconductors could enable a new era of ultra-low-power, high-speed, and multifunctional electronics that meet the demands of AI, 6G

communications, flexible wearables, and energy-efficient data centers in the coming decades.

References

Ahmed, F., & Sun, Z. (2023). High-quality hybrid dielectric materials for 2D electronics. *Science China Materials*, *66*(10).

Ao, M., Zhou, X., Kong, X., Gou, S., Chen, S., Dong, X., Zhu, Y., Sun, Q., Zhang, Z., Zhang, J., ... & Zhou, P. (2025). A RISC-V 32-bit microprocessor based on two-dimensional semiconductors. Nature, 640(8059), 654–661. https://doi.org/10.1038/s41586-025-08759-9

Bernevig, B. A., Fu, L., Ju, L., MacDonald, A. H., Mak, K. F., & Shan, J. (2025). Fractional quantization in insulators from Hall to Chern. *Nature Physics*, *21*(11), 1702–1713. https://doi.org/10.1038/s41567-025-02345-x

Trolle, M. L., Pedersen, T. G., & Véniard, V. (2017). Model dielectric function for 2D semiconductors including substrate screening. *Scientific Reports*, 7, Article 39844. https://doi.org/10.1038/srep39844

Key corrections and notes:

Du, L., Huang, Z., Zhang, J., Ye, F., Dai, Q., Deng, H., Zhang, G., & Sun, Z. (2024). Nonlinear physics of moiré superlattices. *Nature Materials*. https://doi.org/10.1038/s41563-024-01951-8

Han, Z., Xia, Y., Watanabe, K., Taniguchi, T., Mak, K. F., & Shan, J. (2025). Quantum oscillations between excitonic and quantum spin Hall insulators in moiré WSe2. *Preprint*.

Huang, S. (2020, October 26). *Tailoring 2D materials to improve electronic and optical devices*. Penn State College of Engineering. https://www.psu.edu/news/research/story/tailoring-2d-materials-improve-electronic-and-optical-devices

Imec. (2025, December 10). *Imec advances 2D material device technology for future logic scaling*. eeNews Europe. https://www.eenewseurope.com/en/imec-advances-2d-material-device-technology-for-future-logic-scaling/

Jiang, J., Wu, P., Liu, Y., Kong, J., & Peng, L.-M. (2025). Towards fab-compatible two-dimensional electronics. *Nature Reviews Electrical Engineering*, *2*, 6–8. https://doi.org/10.1038/s44287-024-00123-x

Kurpas, M., Faria Junior, P. E., Gmitra, M., & Fabian, J. (2019). Spin-orbit coupling in elemental two-dimensional materials. *Physical Review B*, *100*(12), 125422.(https://doi.org/10.1103/PhysRevB.100.125422)

Lau, C. N., Bockrath, M. W., Mak, K. F., & Zhang, F. (2022). Reproducibility in the fabrication and physics of moiré materials. *Nature*, *602*, 41–48. https://doi.org/10.1038/s41586-021-04173-z

Odebowale, A., Berhe, A. M., & Hattori, H. T. (2025, May 29). Advances in 2D photodetectors: Materials, mechanisms, and applications [Preprint]. Preprints.org. https://doi.org/10.20944/preprints202505.2345.v1

O'Brien, K. P., Naylor, C. H., Dorow, C., Maxey, K., Penumatcha, A. V., Vyatskikh, A., ... & Chau, R. (2023). Process integration and future outlook of 2D transistors. Nature Communications, 14, Article 6400. https://doi.org/10.1038/s41467-023-41779-5

Qin, B., et al. (2025). Two-dimensional indium selenide wafers for integrated electronics. *Science*, *389*, 299–302. https://doi.org/10.1126/science.ade38b

Qin, L., & Wang, L. (2025). Two-dimensional materials: The ultimate solution for future electronics and very large-scale integrated circuits. *Nature Electronics Community*.

Rice University. (2025, November 14). *Breakthrough shows light can move atoms in 2D semiconductors*. ScienceDaily. https://www.sciencedaily.com/releases/2025/11/251114041155.htm

Tan, C., Tang, J., Gao, X., Xue, C., & Peng, H. (2025). 2D bismuth oxyselenide semiconductor for future electronics. *Nature Reviews Electrical Engineering*, *2*, 494–513.

Xia, Y., Han, Z., Zhu, J., Zhang, Y., Knüppel, P., Watanabe, K., Taniguchi, T., Mak, K. F., & Shan, J. (2026). Bandwidth-tuned Mott transition and superconductivity in moiré WSe2. *Nature*, *650*(8102), 585–591. https://doi.org/10.1038/s41586-026-04567-x

Xu, F., Yin, Z., & Tang, A. (2025, November 4). White light-emitting diodes: A breakthrough in efficiency. *Science Bulletin*. https://doi.org/10.1016/j.scib.2025.11.001

Zhao, M., & Chen, Q. (2025). Spintronic devices upon 2D magnetic materials and heterojunctions. *ACS Nano*. https://doi.org/10.1021/acsnano.4c14168

Plummer, D. Z., D'Alessandro, E., & Hattori, H. T. (2025). 2D spintronics for neuromorphic computing with scalability and energy efficiency. Journal of Low Power Electronics and Applications, 15(2), Article 16. https://doi.org/10.3390/jlpea15020016

Kim, J., Son, H., Cho, D. J., Geng, B., Regan, W., Shi, S., Kim, K., Zettl, A., Shen, Y.-R., & Wang, F. (2012). Electrical control of optical plasmon resonance with graphene. Nano Letters, 12(11), 5598–5602. https://doi.org/10.1021/nl302656d

Chandel, M., Rosenkranz, A., Moraru, D., Woźniak, A., & Jastrzębska, A. M. (2025). Measuring the Future–Nanometrology for Advanced Manufacturing of Miniaturized Devices. Advanced Functional Materials, 35(45), 2501663.

Das, S., Pandey, D., Thomas, J., & Roy, T. (2019). The role of graphene and other 2D materials in solar photovoltaics. Advanced Materials, 31(1), 1802722.

Chia, X., & Pumera, M. (2018). Layered transition metal dichalcogenide electrochemistry: journey across the periodic table. Chemical Society Reviews, 47(15), 5602-5613.

Chernozatonskii, L. A., & Artyukh, A. A. (2018). Quasi-two-dimensional transition metal dichalcogenides: structure, synthesis, properties, and applications. Physics–Uspekhi, 61(1), 2-28.

Chowdhury, T., Sadler, E. C., & Kempa, T. J. (2020). Progress and prospects in transition-metal dichalcogenide research beyond 2D. Chemical reviews, 120(22), 12563-12591.

Zhang, M., Biesold, G. M., & Lin, Z. (2021). A multifunctional 2D black phosphorene-based platform for improved photovoltaics. Chemical Society Reviews, 50(23), 13346-13371.

Zollner, K., Kurpas, M., Gmitra, M., & Fabian, J. (2025). First-principles determination of spin–orbit coupling parameters in two-dimensional materials. Nature Reviews Physics, 7(5), 255-269.

Bordoloi, A., Garcia-Castro, A. C., Romestan, Z., Romero, A. H., & Singh, S. (2024). Promises and technological prospects of two-dimensional Rashba materials. Journal of Applied Physics, 135(22).

Lin, X., Rouzhahong, Y., Liang, C., Yuan, J., Yao, S., & Li, H. (2025). Rashba spin-orbit coupling effects on piezoelectric properties of two-dimensional Janus materials. Physical Review B, 111(19), 195432.

Liu, Y., Zeng, C., Zhong, J., Ding, J., Wang, Z. M., & Liu, Z. (2020). Spintronics in two-dimensional materials. Nano-Micro Letters, 12(1), 93.

Di, J., Xiong, J., Li, H., & Liu, Z. (2018). Ultrathin 2D photocatalysts: electronic-structure tailoring, hybridization, and applications. Advanced materials, 30(1), 1704548.

Yagmurcukardes, M., Qin, Y., Ozen, S., Sayyad, M., Peeters, F. M., Tongay, S., & Sahin, H. (2020). Quantum properties and applications of 2D Janus crystals and their superlattices. Applied Physics Reviews, 7(1).

Sun, M., Chou, J. P., Gao, J., Cheng, Y., Hu, A., Tang, W., & Zhang, G. (2018). Exceptional optical absorption of buckled arsenene covering a broad spectral range by molecular doping. ACS omega, 3(8), 8514-8520.

Xu, T., Shen, Y., Yin, K., & Sun, L. (2019). Precisely monitoring and tailoring 2D nanostructures at the atomic scale. APL Materials, 7(5).

Andrade, E., López-Urías, F., & Naumis, G. G. (2023). Topological origin of flat bands as pseudo-Landau levels in uniaxial strained graphene nanoribbons and induced magnetic ordering due to electron-electron interactions. Physical Review B, 107(23), 235143.

Peng, Z., Chen, X., Fan, Y., Srolovitz, D. J., & Lei, D. (2020). Strain engineering of 2D semiconductors and graphene: from strain fields to band-structure tuning and photonic applications. Light: Science & Applications, 9(1), 190.

Qi, Y., Sadi, M. A., Hu, D., Zheng, M., Wu, Z., Jiang, Y., & Chen, Y. P. (2023). Recent progress in strain engineering on van der Waals 2D materials: Tunable electrical, electrochemical, magnetic, and optical properties. Advanced Materials, 35(12), 2205714.

Yang, S., Chen, Y., & Jiang, C. (2021). Strain engineering of two-dimensional materials: Methods, properties, and applications. InfoMat, 3(4), 397-420.

Hong, H., Wu, C., Zhao, Z., Zuo, Y., Wang, J., Liu, C., ... & Xiong, J. (2021). Giant enhancement of optical nonlinearity in two-dimensional materials by multiphoton-excitation resonance energy transfer from quantum dots. Nature Photonics, 15(7), 510-515.

Bhowmik, S., Ghosh, A., & Chandni, U. (2024). Emergent phases in graphene flat bands. Reports on Progress in Physics, 87(9), 096401.

Po, H. C., Zou, L., Vishwanath, A., & Senthil, T. (2018). Origin of Mott insulating behavior and superconductivity in twisted bilayer graphene. Physical Review X, 8(3), 031089.

Regan, E. C., Wang, D., Paik, E. Y., Zeng, Y., Zhang, L., Zhu, J., ... & Wang, F. (2022). Emerging exciton physics in transition metal dichalcogenide heterobilayers. Nature Reviews Materials, 7(10), 778-795.

Herrera-González, S. A., Lara-García, H. A., Pirruccio, G., Ruiz-Tijerina, D. A., & Camacho-Guardian, A. (2025). Moiré excitons and exciton–polaritons: a review. Journal of Physics: Condensed Matter, 37(48), 483002.

Yi, Z. J., Wu, M., Pang, Y., Jia, R., & Xu, R. R. (2021). Non-local dielectric screening effects in phosphorene/g-C3N4 heterojunctions. Applied Surface Science, 567, 150842.

Zheng, Y. J., & Arramel. (2021). Screening Effects at Organic–2D Material Heterointerfaces. Surface Review and Letters, 28(08), 2140008.

Mughnetsyan, V., Manaselyan, A., Movsisyan, A., & Kirakosyan, A. (2024). Effect of two-dimensional non-local screening on characteristics of transition metal dichalcogenide monolayers. Semiconductor Science and Technology, 39(4), 045016.

Yao, B., Liu, Y., Huang, S. W., Choi, C., Xie, Z., Flor Flores, J., ... & Wong, C. W. (2018). Broadband gate-tunable terahertz plasmons in graphene heterostructures. Nature Photonics, 12(1), 22-28.

Venkatesan, K. K., & Samikannu, S. (2026). Intelligent Data-Driven Modeling of SARS-CoV-2 Interactions in BP–MXene–BP Heterostructure SPR Biosensors using Ridge Regression Model. In ITM Web of Conferences (Vol. 82, p. 03023). EDP Sciences.

Eguchi, M., Han, M., Asakura, Y., Hill, J. P., Henzie, J., Ariga, K., ... & Yamauchi, Y. (2023). Materials Space-Tectonics: Atomic-level Compositional and Spatial Control Methodologies for Synthesis of Future Materials. Angewandte Chemie, 135(46), e202307615.

Yan, Q., & Kanatzidis, M. G. (2022). High-performance thermoelectrics and challenges for practical devices. Nature materials, 21(5), 503-513.

Chaudhuri, D., & Nag, A. (2026). 2D Materials for Post-CMOS Electronics: Opportunities, Challenges, and a Holistic Roadmap. Next-Generation High-Speed Electronics and Optoelectronics: Volume 2, 329-354.

Rakheja, S., Chen, Z., & Chen, C. T. (2023). Guest Editorial: Dimensional Scaling of Material Functional Properties to Meet Back-End-of-Line (BEOL) Challenges. Applied Physics Letters, 123(3).

Matzelle, M. E. (2023). Anomalous Intense Coherent Secondary Photoemission and Antiferromagnets: Spintronic Applications, Topological Insulators and Superconductors (Doctoral dissertation, Northeastern University).

Huh, W., Lee, D., & Lee, C. H. (2020). Memristors based on 2D materials as an artificial synapse for neuromorphic electronics. Advanced Materials, 32(51), 2002092.