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Novel Physical Mechanisms in Electronic Materials: Opportunities for Next-Generation Devices

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Abstract

People are now at the beginning of the age of electronic materials where device performance is determined not only by charge transport but also by the intentional use of quantum confinement, spin, topology, ionic motion, phase transitions, ferroelectric polarization and correlated many-body states. This review discusses emergent physical mechanisms defining the prospects for next generation devices beyond traditional silicon scaling. The review covers eight families of mechanisms: 2D semiconductors and van der Waals interfaces, spin-valley physics, topological surface and edge transport, spin-orbit torques and magnetic textures, permissive ionic-electronic coupling, phase-change materials, ferroelectric switching and negative capacitance, and moiré flat-band engineering. These mechanisms are evaluated with regards to device opportunity, manufacturability and remaining barriers. The bottom line is that no one family of materials is going to replace silicon in a heroic parade. A more plausible prospect is heterogeneous integration, where traditional CMOS provides dense logic while novel materials enable nonvolatile state retention, steep-slope switching, local computer-memory coupling, photonic programmability, adaptive sensing and quantum functionality. In the short term, the most promising candidates are ferroelectric hafnium oxide devices, resistive or phase-change in-memory computing elements, 2D semiconductor channels for extreme electrostatic control and spintronic memory or logic blocks. Longer-term opportunities include topological interconnects, allotonic information processing and moiré quantum simulators, if problems of materials uniformity, contact resistance, variability, thermal budgets and circuit-level reliability are resolved.

Keywords: electronic materials; 2D semiconductors; spintronics; topological insulators; memristors; phase-change materials; ferroelectrics; negative capacitance; moiré materials; neuromorphic computing

Introduction

The history of success in microelectronics has been to make the metal-oxide-semiconductor field-effect transistor smaller, cheaper, and more reliable. That scaling strategy remains powerful, but it is no longer a free lunch, because atomically thin bodies, quantum tunnelling, heat, variability and interconnect energy all penalize naïve dimensional reduction. As a result, materials research has moved from the notion that solids are passive conductors, insulators and semiconductors, to the idea that they are active physical systems with internal degrees of freedom that can be utilized for computation, memory and sensing. The electron charge remains relevant but it is now accompanied by spin, valley index, polarization, phase state, topology, ionic position and collective electronic order. Apparently one particle wasn't enough drama for civilization, so materials engineers gave it extra personalities.

The advent of graphene has proven that high quality electronic transport can be sustained in stable atomically thin crystals under ambient conditions (Novoselov et al., 2004). The continued development of van der Waals heterostructures revealed that layered materials could be assembled into designer stacks without the same lattice matching constraints as traditional epitaxy (Geim & Grigorieva, 2013; Novoselov et al., 2016). Monolayer transition metal dichalcogenides, such as MoS2, then added a critical ingredient missing from graphene for logic: a large bandgap and strong electrostatic control, as shown by early single-layer MoS2 transistors (Radisavljevic et al., 2011). Simultaneously, spintronics, topological materials, ferroelectrics, permissive oxides and phase-change materials progressed from niche research areas to device platforms with plausible connections to memory, logic and computing architectures.

In this review we take a practical question: what physical mechanisms in electronic materials offer defensible opportunities for next generation devices? The answer isn't a list of trendy materials, because fashion in science is just a funding cycle in a lab coat. Instead, viable prospects require a chain of logic from physical mechanism to measurable device behavior, from device behavior to circuit architecture, and from architecture to manufacturability. The review is therefore concerned with mechanisms rather than with isolated materials. It compares physical origin, enabling materials, device opportunities and barriers, and argues that the most realistic pathway is not replacement of CMOS but co-integration of new materials with CMOS-compatible process modules.

Scope and Review Logic

The literature base selected for this review prioritizes peer-reviewed papers and widely cited reviews that connect physical mechanisms to device operation. The scope deliberately covers materials that differ in maturity. Hafnium oxide ferroelectrics, phase-change memories and spin-torque magnetic devices are closer to product-oriented integration. 2D semiconductors are maturing rapidly but remain constrained by contacts, dielectrics and large-area uniformity. Topological, valleytronic and moiré platforms are more exploratory, but they are important because they introduce new information carriers and new forms of protected or tunable transport. The comparison is therefore not a ranking of glamour. It is a sanity check, which science occasionally requires.

The paper uses the term novel physical mechanism to describe a controllable microscopic or mesoscale material response that can perform a device-relevant function more efficiently or differently than charge-only semiconductor switching. Examples include spin-momentum locking in topological materials, valley-selective optical transitions in monolayer TMDs, filament formation in resistive memories, reversible amorphous-crystalline transitions in phase-change compounds, and negative capacitance during ferroelectric polarization dynamics. Novelty alone is insufficient. The mechanism must map to a device function such as switching, state retention, signal modulation, sensing, analog weighting, quantum coherence or energy-efficient interconnect. Figure 1 summarizes this mechanism-to-device logic.

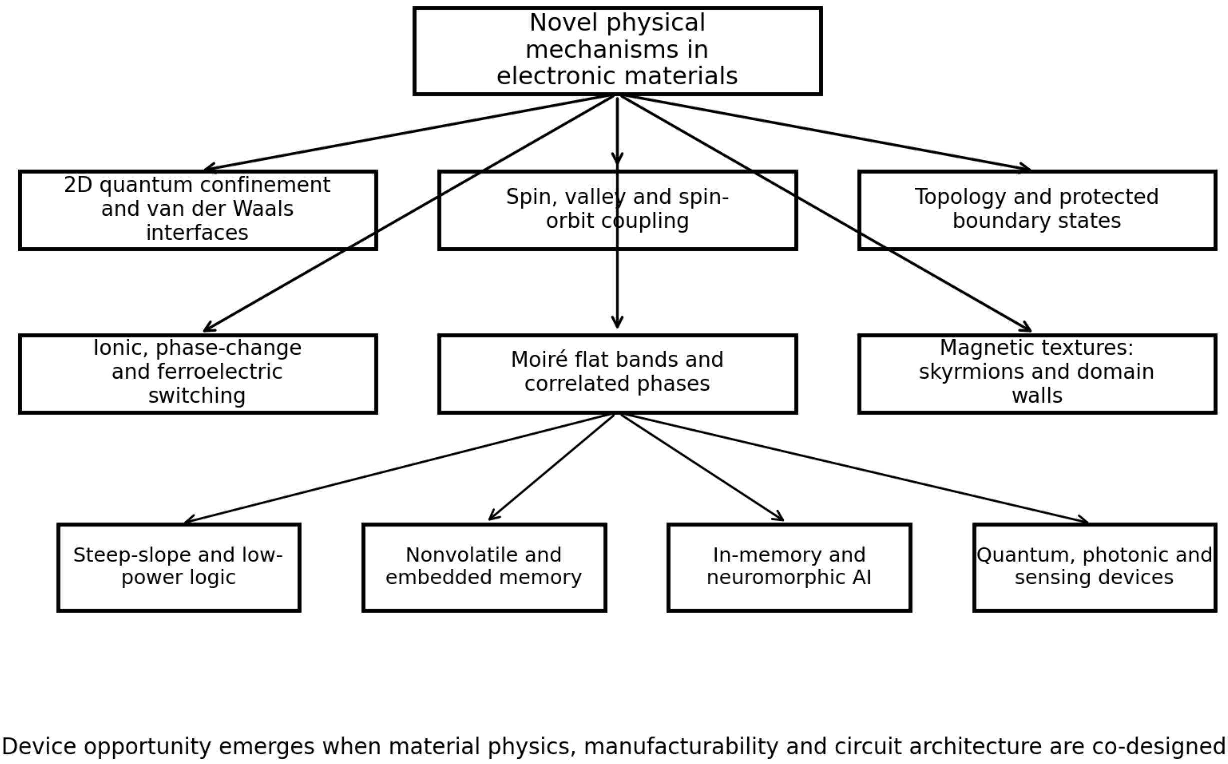

Figure 1: Mechanism-to-device map for next-generation electronic materials, Source: Author Generated

Two-Dimensional Semiconductors and Van der Waals Interfaces

Two-dimensional semiconductors provide the clearest example of a material mechanism that directly responds to the limits of transistor scaling. When a semiconductor channel becomes only one or a few atomic layers thick, the gate can control the channel potential more effectively, suppressing short-channel effects. Monolayer TMDs also avoid the dangling-bond-rich surfaces of many conventional thin semiconductors because their basal planes are naturally passivated. The early demonstration of single-layer MoS2 transistors reported strong current modulation in an atomically thin channel, establishing the feasibility of 2D semiconductor field-effect devices (Radisavljevic et al., 2011). Reviews of TMD electronics emphasize that these materials combine thickness scaling with band gaps, optical activity and mechanical flexibility, making them candidates for logic, optoelectronics and flexible electronics (Wang et al., 2012).

The physical mechanism is not simply that the material is thin. Quantum confinement changes the band structure, dielectric screening becomes nonlocal, excitons become strongly bound, and interfaces dominate transport. Mak et al. (2010) showed that MoS2 changes from an indirect-gap material in bulk to a direct-gap semiconductor in the monolayer limit, which explains its strong light emission and optoelectronic relevance. Van der Waals stacking further allows tunneling junctions, resonant tunneling diodes, light-emitting devices and multifunctional heterostructures without forcing conventional epitaxial lattice matching (Geim & Grigorieva, 2013; Novoselov et al., 2016). The practical opportunity is to use

2D semiconductors as ultra-thin channels in advanced logic and as active layers in flexible sensors and optoelectronic devices.

The barriers are equally physical. Contact resistance is a stubborn tax collector. Because current must enter an atomically thin semiconductor, metal-induced gap states, Schottky barriers, Fermi-level pinning and edge disorder can dominate performance. Dielectric integration is another major obstacle: high-k gate dielectrics must be deposited without damaging or contaminating the 2D surface. Large-area synthesis must also achieve wafer-scale uniformity in thickness, grain boundaries, strain and defect density. Therefore, 2D semiconductors are promising not because they magically outperform silicon everywhere, but because they attack a specific scaling problem: electrostatic control at the atomic thickness limit.

Spin-Valley Coupling and Valleytronic Functions

Monolayer TMDs also introduce spin-valley physics. In materials such as MoS2 and WSe2, broken inversion symmetry and strong spin-orbit coupling produce inequivalent K and K' valleys in momentum space. The valley index can behave like an information degree of freedom, and optical selection rules allow circularly polarized light to address different valleys. Xiao et al. (2012) showed that inversion symmetry breaking and spin-orbit coupling create coupled spin and valley physics in monolayer group-VI dichalcogenides, enabling valley Hall and spin Hall effects. Xu et al. (2014) reviewed the rapid development of spin and pseudospin control in layered TMDs, connecting optical selection rules, valley polarization and coherent control.

The device opportunity is attractive but still speculative. Valleytronic devices could encode information in valley polarization rather than charge density, potentially reducing dissipation in some operations. The physics also supports circularly polarized light emitters, valley filters, valley Hall sensors and hybrid spin-valley quantum devices. However, valley polarization must survive disorder, phonons, intervalley scattering and imperfect interfaces. Valley devices also require circuit concepts that read, write and process valley states without converting every operation back to ordinary charge. Otherwise, the supposed new information carrier simply becomes a detour, and engineers already have enough detours, mostly named after committees.

Spin-orbit and spin-valley coupling are also relevant because they bridge 2D semiconductors with spintronics and topological materials. In the long term, heterostructures combining ferromagnets, TMDs, topological layers and superconductors may allow electrical and optical control of coupled spin, charge and valley states. The more immediate role of spin-valley physics may be in optoelectronics, quantum emitters, sensing and specialized logic primitives rather than general-purpose digital logic.

Topological Electronic States

Topological electronic materials exploit a different physical idea: global band structure properties can enforce conducting states at boundaries while the bulk remains insulating. Kane and Mele (2005) proposed the quantum spin Hall effect in graphene, connecting spin-orbit coupling to protected helical edge states. Bernevig, Hughes and Zhang (2006) then predicted the quantum spin Hall effect in HgTe quantum wells, a result that pushed topology from mathematical elegance toward semiconductor materials. Reviews by Hasan and Kane (2010) and Qi and Zhang (2011) established the broader framework of topological insulators and topological superconductors.

The device attraction is obvious. If boundary states are protected against certain forms of backscattering, they may enable low-dissipation interconnects, spin-polarized channels and fault-tolerant quantum states. Topological surface states also exhibit spin-momentum locking, which can efficiently convert charge current into spin accumulation. This makes topological materials relevant to spin-orbit torque devices and magnetic switching. The long-term connection to topological superconductivity and Majorana modes has also made topological materials central to quantum computing proposals (Qi & Zhang, 2011).

The realism check is less glamorous. Topological protection does not abolish contact resistance, disorder, bulk leakage, phonons, materials defects or fabrication headaches. Many topological insulators suffer from unintentional bulk conduction, and the protected state may not dominate transport in practical devices. Room-temperature operation and integration with CMOS process flows remain major problems. The credible opportunity is therefore not a universal topological wire that rescues electronics from entropy. It is more likely to be hybrid devices where topology improves spin conversion, interfacial transport, quantum states or specialized sensing under carefully controlled conditions.

Spin-Orbit Torque, Magnetic Order and Skyrmions

Spintronic materials use electron spin and magnetic order as functional variables. Spintronics is not new, but its physical mechanisms continue to expand into spin-orbit torques, antiferromagnetic dynamics, magnonics and topological magnetic textures. Žutić, Fabian and Das Sarma (2004) framed the field around spin generation, spin injection, spin dynamics and spin-polarized transport. Current-induced spin-orbit torque has since become especially important because it allows electrical switching of magnetization through angular momentum transfer from spin-orbit-coupled systems (Manchon et al., 2019).

The most mature opportunity is nonvolatile memory. Magnetic tunnel junctions already demonstrate that resistance can depend on magnetic orientation, allowing information to be stored without continuous power. More novel prospects include spin-orbit torque memory, domain-wall devices, spin-torque oscillators and probabilistic bits for stochastic computing. Magnetic skyrmions expand this toolkit. Nagaosa and Tokura (2013) reviewed skyrmions as nanoscale topological spin textures, while Fert, Reyren and Cros (2017) emphasized their potential for storage, logic and neuromorphic devices. Skyrmions are attractive because they can be small, mobile and topologically stable, although topological stability should not be confused with industrial reliability. The universe enjoys loopholes.

Spintronic mechanisms are especially valuable where nonvolatility, endurance and radiation tolerance matter. They also suit edge systems that require instant-on operation and low standby power. The obstacles are current density, write energy, thermal stability, material stack complexity, stochastic switching distributions, read-disturb risks and integration with back-end-of-line process temperatures. Spintronic devices therefore have a strong memory and accelerator role, but their broad use in logic will require better switching efficiency and device-architecture co-design.

Memristive Ionic-Electronic Coupling

Memristive and resistive-switching devices use coupled ionic and electronic motion to alter conductance. The influential titanium dioxide memristor model showed that memristance can arise when ionic drift changes a nanoscale resistance profile under bias (Strukov et al., 2008). Since then, oxide-based resistive random-access memories, conductive-bridge devices, electrochemical metallization cells and other memristive systems have been explored for nonvolatile memory and analog computing. Zidan, Strachan and Lu (2018) argued that memristive systems could affect on-chip storage, biologically inspired computing and in-memory computing if reliability and scaling challenges are addressed.

The main physical appeal is local statefulness. A two-terminal device can store conductance as a material state, and dense crossbar arrays can perform matrix-vector multiplication using Ohm's law and Kirchhoff's current summation. This is why memristors are repeatedly proposed for neural-network accelerators, where analog weights can be stored close to computation. Ielmini and Wong (2018) reviewed in-memory computing with resistive switching devices, emphasizing the reduction of costly data transfer between processor and memory. Sebastian et al. (2020) compared memory devices for in-memory computing and identified key primitives such as multiply-accumulate, logic-in-memory and stochastic computation.

The challenge is that the same physics that makes memristors interesting also makes them disobedient. Ionic motion, filament formation, redox reactions and trap dynamics produce variability, drift, nonlinear updates, limited endurance and temperature dependence. In biological terms this may sound charming; in semiconductor manufacturing terms it sounds like a lawsuit waiting for a yield engineer. Progress will require better materials control, selector devices, write-verify schemes, error-tolerant algorithms and circuit-level compensation. The near-term opportunity is not replacing all digital computing. It is accelerating selected workloads, especially analog AI inference, optimization and local learning, where device imperfections can be tolerated or exploited.

Phase-Change and Photonic-Electronic Materials

Phase-change materials use reversible switching between amorphous and crystalline states to store information. The two states differ in electrical resistance and optical properties. This is a powerful mechanism because the state is nonvolatile and can be changed by short electrical or optical pulses. Phase-change memory has been developed for storage-class memory, while photonic phase-change devices exploit changes in refractive index for optical modulation and memory. Wuttig, Bhaskaran and Taubner (2017) reviewed phase-change materials for nonvolatile photonic applications, showing that the same atomic rearrangement can be useful in light-based devices.

In-memory computing provides another opportunity. Phase-change conductance can act as an analog weight in a computational memory array. Ríos et al. (2019) demonstrated in-memory computing on a photonic platform using phase-change materials, connecting nonvolatile multilevel optical states with direct photonic multiplication. This matters because data movement is one of the central energy costs in modern computing. If memory elements also compute, electronic and photonic architectures can reduce transfer overhead.

Yet phase-change materials face drift, resistance noise, programming energy, thermal cross-talk and endurance limits. Crystallization and amorphization are thermally driven processes, so device geometry, heat confinement and materials engineering are crucial. Photonic devices must also manage insertion loss, optical contrast and integration with silicon photonics. The prospects are strong in specialized memory, photonic computing, reconfigurable optics and AI accelerators, especially when the system can tolerate analog nonidealities and use calibration.

Ferroelectric Switching and Negative Capacitance

Ferroelectric materials possess switchable spontaneous polarization. In devices, polarization can modulate channel conductance, tunnel current, capacitance or resistance. The discovery of ferroelectricity in doped hafnium oxide thin films was particularly important because HfO2 is already familiar to CMOS manufacturing (Böscke et al., 2011). Mikolajick et al. (2021) argued that hafnium oxide-based ferroelectrics and AlScN are among the most promising ferroelectric materials for semiconductor process integration. This is a rare case where a genuinely interesting material does not immediately scream, "please build a new factory from scratch."

Ferroelectric field-effect transistors can function as nonvolatile memories, where polarization state controls the channel. Ferroelectric tunnel junctions can act as multilevel resistive elements. Negative-capacitance field-effect transistors aim to exploit the unstable region of a ferroelectric energy landscape to provide internal voltage amplification and reduce subthreshold swing. Salahuddin and Datta (2008) proposed the use of negative capacitance for low-power nanoscale devices, and Khan et al. (2015) reported negative capacitance in a ferroelectric capacitor. The attraction is direct: if switching can occur at lower supply voltage, logic energy can be reduced.

Still, negative capacitance has been controversial because measured steep slopes and voltage amplification can be affected by domains, hysteresis, leakage, transient effects and measurement artifacts. Ferroelectric HfO2 also faces wake-up, fatigue, imprint, coercive-field and retention challenges. The credible near-term prospects are embedded nonvolatile memory, ferroelectric analog synapses and low-power logic assists, not a magical end to power dissipation. Ferroelectrics are best viewed as stateful, CMOS-compatible materials that can be inserted into memory and computing architectures where nonvolatility and tunable polarization matter.

Moiré Flat Bands and Correlated Electronic Phases

Moiré materials introduce a newer design variable: twist angle. When two layered crystals are rotationally misaligned, the resulting long-wavelength moiré pattern modifies the electronic band structure. Bistritzer and MacDonald (2011) predicted that twisted bilayer graphene could host flat bands at magic angles. Experiments later found correlated insulator behavior and unconventional superconductivity in magic-angle graphene superlattices (Cao et al., 2018a, 2018b). Andrei and MacDonald (2020) reviewed how twisted graphene bilayers became a tunable platform for correlated two-dimensional electron systems.

The physical mechanism is bandwidth engineering. When bands flatten, kinetic energy is suppressed and electron-electron interactions dominate. This enables correlated insulators, superconductivity, magnetism and anomalous Hall states under gate control. Such tunability is extraordinary for fundamental physics and quantum simulation. Moiré systems also point toward devices where electronic phases are programmed by twist, pressure, displacement field, carrier density and dielectric environment.

Near-term commercial electronics is another matter. Twist-angle disorder, microscopic strain, small device area, low-temperature operation and fabrication reproducibility are severe barriers. Moiré materials are therefore best classified as high-science, long-horizon platforms. Their device value may first appear in quantum simulation, tunable superconducting or magnetic devices, and quantum sensors rather than mainstream processors. The opportunity is intellectually enormous; the manufacturability is currently less enthusiastic.

Mechanism family	Physical origin	Representative materials	Device prospects
2D semiconductor transport	Atomic-thickness electrostatics, quantum confinement and van der Waals surfaces.	MoS_2, WS_2, WSe_2, black phosphorus, graphene heterostructures.	Scaled logic channels, tunneling devices, flexible sensors and optoelectronics.
Spin-valley coupling	Broken inversion symmetry and strong spin-orbit coupling create valley-selective states.	Monolayer TMDs such as MoS_2 and WSe_2.	Valley filters, circularly polarized emitters, optoelectronic memory and quantum interfaces.
Topology	Band inversion and topological invariants protect edge or surface states.	HgTe quantum wells, Bi_2Se_3-family materials, topological heterostructures.	Spin conversion, low-dissipation channels, quantum devices and topological sensing.
Spin-orbit and skyrmion dynamics	Current-induced spin torques and chiral magnetic textures.	Magnetic tunnel junctions, heavy-metal/ferromagnet stacks, multilayers.	MRAM, domain-wall logic, stochastic bits, skyrmion racetracks and oscillators.
Memristive switching	Bias-driven ionic migration, redox reactions and conductive filament modulation.	HfO_2, TiO_2, TaO_x, Ag/Cu-based electrochemical cells.	RRAM, analog synapses, crossbar accelerators and stochastic computing.
Phase-change switching	Reversible amorphous-crystalline transitions with electrical and optical contrast.	GST, doped chalcogenides and photonic PCM stacks.	Storage-class memory, in-memory computing and reconfigurable photonics.
Ferroelectric polarization	Switchable spontaneous polarization, domain dynamics and negative capacitance.	Doped HfO_2, $Hf_{0.5}Zr_{0.5}O_2$, AlScN.	FeFET memory, ferroelectric tunnel junctions, steep-slope logic and neuromorphic synapses.
Moiré correlated phases	Twist-angle-induced flat bands amplify electron correlation.	Magic-angle graphene and van der Waals moiré superlattices.	Quantum simulation, tunable superconductivity, correlated electronics and quantum sensing.

Table 1: Major mechanism families, physical origins and device prospects, Source: Author Generated

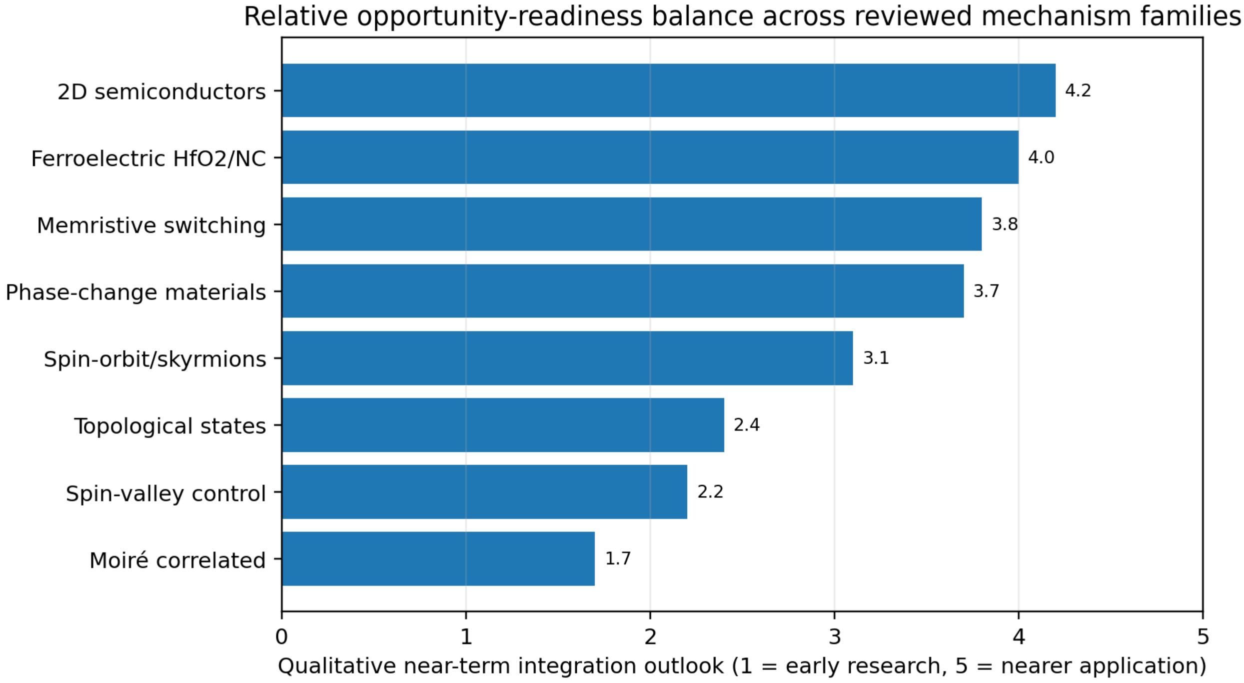

Figure 2: Qualitative near-term integration outlook. Scores are literature-informed estimates, not measured technology-readiness levels, Source: Author Generated

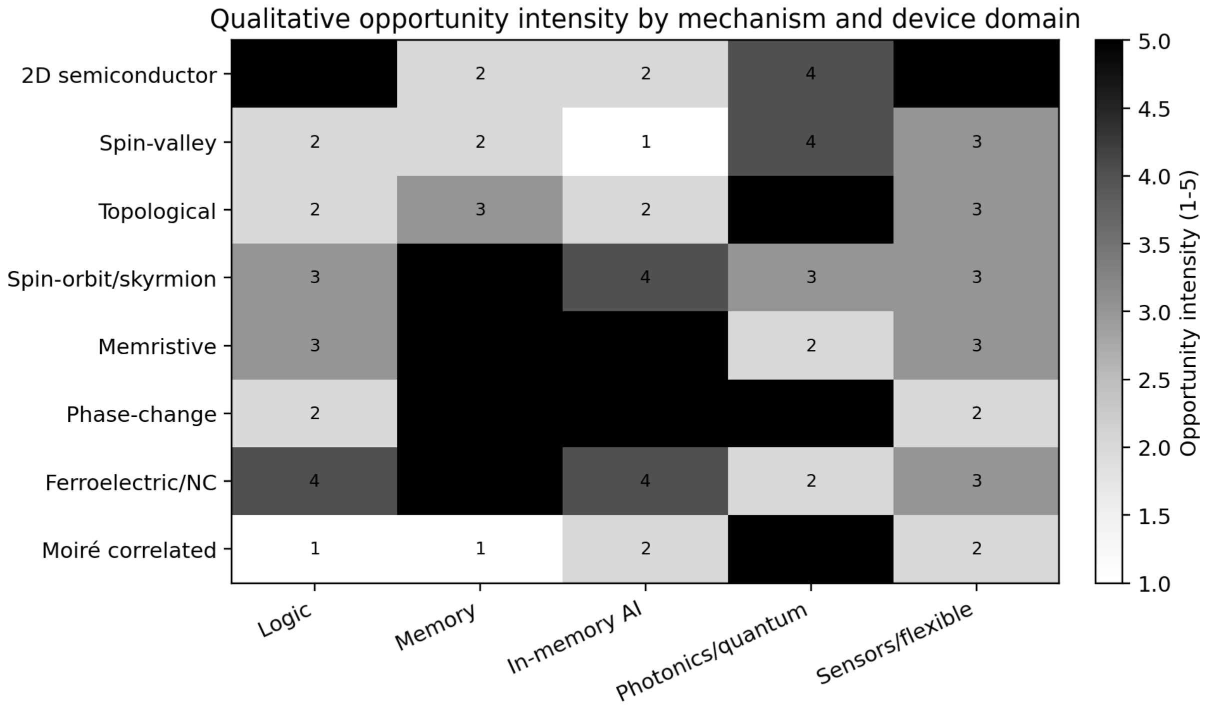

Figure 3: Qualitative opportunity intensity matrix across mechanisms and device domains, Source: Author Generated

Device Opportunities Across Mechanisms

Across these mechanisms, four device opportunities stand out. The first is low-power logic extension. 2D semiconductor channels can improve gate control, while ferroelectric negative capacitance may reduce effective switching voltage. These mechanisms are not substitutes for transistor engineering; they are additions to it. Their success depends on whether they improve energy-delay-area trade-offs after contacts, parasitics, variability and integration are included.

The second opportunity is nonvolatile memory. Spintronic, ferroelectric, phase-change and resistive-switching materials all provide material-state retention without continuous power. Each mechanism offers a different trade-off. Magnetic devices emphasize endurance and nonvolatility, ferroelectrics emphasize speed and CMOS compatibility, phase-change devices emphasize multilevel storage and photonic compatibility, and memristive devices emphasize density and analog weight storage. Table 1 compares the main physical bases and device prospects. The annoying conclusion, because nature refuses to provide simple shopping lists, is that each memory type has a niche rather than a universal victory.

The third opportunity is in-memory and neuromorphic computing. Data movement consumes substantial energy in modern architectures; stateful materials can compute locally by exploiting their own physics. Resistive and phase-change crossbars can perform multiply-accumulate operations, ferroelectric devices can implement analog synapses, and spintronic devices can support stochastic or oscillator-based computing. These are not merely smaller transistors. They are device-architecture co-design platforms.

The fourth opportunity is quantum, photonic and adaptive sensing. Topological materials offer protected or spin-polarized states, TMDs offer excitonic and valley-selective optics, phase-change materials offer reconfigurable photonics, and moiré systems offer tunable correlated phases. These domains may not require replacing CMOS logic; instead, they benefit from integration beside CMOS readout, control and communication circuits. In other words, the future device stack will probably be a layered compromise, which is exactly what humans build when physics refuses to be tidy.

Barriers, Manufacturability and Research Priorities

The credibility of next-generation electronic materials depends on five cross-cutting challenges. First, materials uniformity must move from beautiful flakes and small prototypes to wafer-scale reproducibility. This is especially critical for 2D semiconductors and moiré systems, where atomic thickness, grain boundaries and twist-angle variations strongly affect performance. Second, interfaces must be engineered as active parts of the device, not as afterthoughts. Contacts, dielectrics, ferromagnet interfaces, tunnel barriers and thermal boundaries often control the measured response more than the ideal bulk mechanism.

Third, variability must be handled at the device, circuit and algorithm levels. Memristive and phase-change devices are intrinsically history-dependent; ferroelectric domains switch statistically; spintronic devices are affected by thermal fluctuations; and 2D devices are vulnerable to local disorder. Variability is not always fatal, especially for probabilistic and neuromorphic systems, but pretending it does not exist is the fastest route to a failed technology demonstrator. Fourth, thermal budget and process compatibility determine whether a material can enter a realistic semiconductor flow. Hafnium oxide ferroelectrics are attractive partly because they connect to existing high-k process knowledge, whereas many quantum and moiré systems remain far from high-volume manufacturing.

Fifth, benchmarking must be architecture-aware. A material that looks impressive in a single device may lose its advantage when selectors, peripheral circuits, write-verify energy, error correction, heat removal and endurance are included. The next-generation device question must therefore be framed at system level: what task becomes more energy efficient, more compact, more adaptive or more reliable because this mechanism exists? Table 2 summarizes major barriers and credible research directions.

Barrier	Most affected mechanisms	Why it matters	Research direction
Wafer-scale uniformity	2D semiconductors, moiré systems, topological films	Thickness, strain, defects and twist-angle variation alter device behavior.	Scalable growth, transfer-free integration, inline metrology and statistical process control.
Contact and interface control	2D devices, spintronic stacks, ferroelectrics, topological materials	Interfaces can dominate injection, tunneling, switching and readout.	Atomically clean contacts, low-damage dielectrics, interface passivation and band-alignment engineering.
Variability and drift	Memristors, phase-change materials, ferroelectrics, spintronic devices	State updates and retention can vary across cycles and cells.	Materials stabilization, write-verify, redundancy, error-aware algorithms and circuit compensation.
Thermal budget compatibility	Ferroelectrics, phase-change materials, 2D layers, magnetic stacks	Back-end process temperature limits can destroy desired phases or interfaces.	Low-temperature deposition, BEOL-compatible annealing and encapsulation strategies.
Architecture-level benchmarking	All mechanism families	Single-device metrics often exaggerate system benefits.	Compare full energy-delay-area-reliability budgets including peripherals and error correction.

Figure 4: Cross-cutting barriers and research directions, Source: Author Generated

Credible Prospects for Next-Generation Devices

Near-term prospects are strongest where new materials can enter existing manufacturing flows or well-defined accelerators. Ferroelectric HfO2 memory, spintronic memory, resistive-switching accelerators, phase-change computational memory and 2D semiconductor channels all have plausible paths because they address concrete device needs. Medium-term prospects include reconfigurable photonics, hybrid spin-orbit devices, flexible 2D sensors and analog in-memory AI modules. Long-term prospects include valley logic, topological quantum devices and moiré correlated-electron hardware.

The most credible research direction is heterogeneous integration. Rather than demanding that one exotic material replace silicon, future devices can assign functions according to physical strength. CMOS remains excellent for dense control logic. Ferroelectrics and spintronics provide nonvolatile state. Memristive and phase-change elements provide local analog computation. 2D materials provide ultra-thin channels and optoelectronic surfaces. Topological and moiré materials provide quantum functionality where their exotic phases are actually needed. This division of labor is less theatrical than a “post-silicon revolution,” but it is more believable, which is a tragedy only for keynote speakers.

A second prospect is physics-aware artificial intelligence hardware. Current AI accelerators are limited by memory movement and energy. Stateful electronic materials can reduce this burden by embedding weights, nonlinearities or stochasticity directly in devices. However, algorithm-hardware co-design is essential. Materials with analog drift and variability will not behave like ideal digital multipliers. They must be used with training schemes, calibration, redundancy and error-resilient model architectures.

A third prospect is adaptive sensing and edge intelligence. Flexible 2D materials, ferroelectric memories, memristive synapses and spintronic stochastic elements can create sensor nodes that store, pre-process and classify data locally. Such systems matter for medical devices, structural monitoring, robotics, distributed environmental sensing and low-power internet-of-things hardware. The opportunity is not just faster computing. It is materials that blur the boundary between sensing, memory and computation.

Conclusion

Novel physical mechanisms in electronic materials are reshaping the device landscape by expanding what can be treated as information. Charge remains central, but spin, valley, polarization, phase, topology, ion configuration and correlated electronic order now provide additional levers. The strongest device prospects are those that connect a physical mechanism to a concrete system bottleneck: power in logic, data movement in AI, standby leakage in memory, reconfigurability in photonics, or sensitivity in sensors.

The review suggests a disciplined optimism. Two-dimensional semiconductors are credible for ultra-scaled channels and optoelectronics, but contacts and dielectrics remain decisive. Spintronic and skyrmion devices are powerful for nonvolatile and stochastic functions, but write energy and integration must improve. Memristive and phase-change materials are strong candidates for in-memory computing, provided variability and endurance are managed. Ferroelectric HfO2 is among the most manufacturable novel materials, but negative capacitance and reliability require careful interpretation. Topological, valleytronic and moiré systems provide some of the richest physics, but their path to manufacturable electronics is longer.

The future of electronic materials will likely be heterogeneous, not monolithic. Instead of replacing CMOS, next-generation materials will be inserted where their physical mechanisms solve specific problems that silicon charge-switching handles poorly. That is less poetic than a revolution, but far more useful. Electronics advances when physics, materials, devices and circuits are forced to cooperate, preferably before the reviewer asks for “one more experiment.”

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