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Two-Dimensional Transition Metal Dichalcogenide Transistors for Flexible Electronics: Progress, Interface Engineering and Reliability Challenges

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Abstract. Flexible electronic systems require semiconductor devices and materials that can provide reliable electrical performance while conforming to curved, moving, or deformable surfaces. Two-dimensional transition metal dichalcogenides, including MoS_2, WS_2, and WSe_2, are promising candidates because their atomically thin structures, semiconducting bandgaps, and mechanically compliant nature are suitable for low-power flexible transistors. This review critically examines how the material properties, fabrication methods, and interface engineering of these semiconductors influence their electrical performance, mechanical durability, and potential for large-scale integration. Recent advances are compared with selected foundational research to evaluate progress from individual field-effect transistors to wafer-scale arrays and functional flexible circuits. The reviewed evidence shows that substantial advances have been made in nanoscale channel fabrication, high-κ dielectric integration, and circuit complexity. However, the technological maturity of flexible TMD electronics remains limited by material non-uniformity, transfer-induced contamination, contact resistance, dielectric defects, unstable p-type behaviour, and insufficiently standardised reliability testing. High performance in selected devices therefore does not necessarily indicate reproducible manufacturing or long-term mechanical stability. Future research should prioritise defect-controlled wafer-scale growth, clean low-temperature integration, mechanically durable interfaces, complementary logic, and statistically meaningful bending tests. TMD transistors are unlikely to replace conventional silicon electronics in the immediate future, but they could complement silicon in transparent, wearable, and conformable low-power systems where mechanical flexibility provides a clear functional advantage.

Keywords: Transition metal dichalcogenides, flexible electronics, field-effect transistors, interface engineering, mechanical reliability

1. Introduction

Flexible electronics are essential for wearables, e-skin, foldable displays, and implantables—where conformability to curved or dynamic surfaces is non-negotiable. While silicon transistors deliver high performance and benefit from mature fabrication, their rigidity and high thermal budget prevent

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direct integration with most flexible polymer substrates. This gap has driven intense interest in alternative semiconductors that merge electrical competence with mechanical compliance.

Two-dimensional transition metal dichalcogenides (TMDs)—especially MoS_2, WS_2, and WSe_2—have emerged as leading candidates for flexible field-effect transistor channels. Their atomic thickness minimizes bending strain; their intrinsic bandgaps enable high on/off ratios and low off-state leakage; and their van der Waals–ready surfaces (lacking dangling bonds perpendicular to the basal plane) simplify integration with diverse substrates and functional layers [1, 2]. Recent advances include nanoscale-channel TMD transistors, wafer-scale arrays, and integrated circuits with >100 devices [3-5]. Yet record-breaking lab results rarely translate to scalable manufacturing: transfer contamination, grain boundaries, contact resistance, dielectric defects, and device variability persistently hinder uniform, large-area integration. Equally critical—and often overlooked—is mechanical reliability: inconsistent bending protocols (radius, cycles, loading mode) across studies impede meaningful comparison [6, 7].

This review critically examines how TMD material properties, fabrication processes, and interface engineering jointly govern electrical performance and mechanical robustness in flexible transistors. Moving beyond peak metrics, we assess recent work by reproducibility, interface quality, bending endurance, and scalability. By synthesizing journal literature, we map progress from single devices to circuits, pinpoint key bottlenecks to industrial adoption, and define priority research directions for reliable, scalable flexible TMD electronics.

2. Material and device fundamentals

2.1. Structure and properties of semiconducting TMDs

Transition metal dichalcogenides have the general chemical formula MX_2, where M represents a transition metal such as molybdenum or tungsten and X represents a chalcogen such as sulphur or selenium. Each layer consists of a plane of metal atoms positioned between two chalcogen planes with strong in-plane covalent bonding, while adjacent layers are held together by relatively weak van der Waals forces. This layered structure allows TMDs to be isolated as atomically thin sheets without creating a high density of out-of-plane dangling bonds.

MoS_2, WS_2, and WSe_2 possess thickness-dependent band structures and bandgaps suitable for transistor switching. MoS_2 is the most extensively investigated because of its environmental stability, established synthesis methods and frequently observed n-type transistor behaviour. WS_2 can also provide strong gate modulation and relatively low off-state current, whereas WSe_2 is particularly important for p-type and ambipolar devices. However, these classifications are not entirely intrinsic because the observed carrier polarity is strongly affected by defects, metal contacts, dielectric interfaces and environmental adsorbates [2, 8]. Material selection must therefore be considered together with the complete device structure.

The atomic thickness of TMD channels provides an important mechanical advantage. During bending, the strain experienced by a layer approximately increases with its distance from the neutral mechanical plane and decreases with increasing bending radius. Placing an atomically thin semiconductor close to this neutral plane can consequently reduce the strain imposed on the channel. Nevertheless, the strength of an isolated monolayer does not guarantee the reliability of a complete transistor. Defects can produce substantial variations in fracture strength and fatigue lifetime, while brittle dielectrics, metal electrodes and weak interfaces may fail before the TMD channel itself [7].

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2.2. Flexible field-effect transistor structure and performance metrics

A typical flexible TMD field-effect transistor consists of source and drain electrodes connected by a semiconducting TMD channel, a gate dielectric, a gate electrode and a flexible supporting substrate. Applying a gate voltage changes the carrier concentration in the channel and therefore controls the current flowing between the source and drain. Device behaviour is commonly evaluated using field-effect mobility, current on/off ratio, threshold voltage, subthreshold swing, contact resistance and operating voltage.

These values must be interpreted cautiously when comparing different studies. Reported mobility can depend on the extraction method and may be underestimated or overestimated if contact resistance is not separated from channel resistance. Similarly, a small bending radius does not by itself demonstrate mechanical reliability. The corresponding strain, device thickness, bending direction, number of loading cycles and retention of electrical performance should also be reported. A meaningful assessment of flexible TMD transistors must therefore combine electrical performance with mechanical durability and statistical device uniformity rather than relying on a single record value.

3. Fabrication and interface engineering

3.1. Material synthesis and transfer

The fabrication route determines whether the intrinsic properties of a TMD can be maintained in a flexible transistor. Mechanical exfoliation generally produces highly crystalline flakes with relatively few grain boundaries and is therefore valuable for investigating fundamental transport behaviour. However, the limited flake size, random thickness and low production yield make this method unsuitable for large-area circuits. Chemical vapour deposition (CVD), by comparison, can enable large-area and, in some cases, wafer-scale growth of continuous monolayer films and is more compatible with device integration. Its advantages are accompanied by defects, including chalcogen vacancies, grain boundaries and spatial variations in layer thickness, which can produce non-uniform carrier mobility and threshold voltage.

Recent advances in epitaxial growth have improved the size and crystallographic alignment of MoS_2 domains. Li et al., for example, demonstrated wafer-scale single-crystal MoS_2 through buffer-layer control [9]. Nevertheless, successful growth on a rigid wafer does not immediately provide a flexible electronic system. Most high-quality TMDs are synthesised at temperatures that exceed the thermal stability of polymer substrates, making transfer to materials such as polyimide, polyethylene terephthalate or polyethylene naphthalate necessary.

Wet-transfer methods are widely used because they are relatively simple and compatible with large films. However, polymer support layers, solvents and capillary forces can introduce residues, wrinkles, cracks and unintended strain. These effects are particularly significant for an atomically thin semiconductor because even small quantities of contamination can modify charge transport. Dry-transfer and device-first approaches can reduce direct chemical exposure, but their alignment, yield and scalability remain challenging. Daus et al. transferred CVD-grown TMDs and pre-patterned contacts together with a polyimide layer, enabling nanoscale flexible transistors while limiting damage associated with processing directly on a flexible substrate [3]. This approach demonstrated the value of transfer engineering, although it still required multiple fabrication stages on a rigid carrier.

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3.2. Metal–semiconductor contacts

Electrical contacts frequently limit the measured performance of TMD transistors. Conventional metal deposition can damage the semiconductor surface, while the metal–TMD interface may form a Schottky barrier that restricts carrier injection. Fermi-level pinning further reduces the ability to control the barrier simply by selecting a metal with a suitable work function. As a result, a transistor may display low current or an apparently low field-effect mobility even when the channel material itself has favourable transport properties [2, 3].

Contact engineering strategies include local doping, phase engineering, graphene electrodes and transferred van der Waals contacts. These methods can reduce contact resistance by improving carrier injection or limiting interfacial disorder. However, the lowest contact resistance reported in an individual device may not represent the most appropriate solution for flexible electronics. The contact must also be deposited at a polymer-compatible temperature, remain stable during repeated bending and be reproducible over a large area. Metal cracking, interfacial sliding and contact delamination can cause electrical degradation even when the TMD channel remains intact. Contact performance should therefore be evaluated before, during and after cyclic deformation.

Contact resistance should be reported separately from channel resistance because it can dominate the total resistance and distort the extracted field-effect mobility. It is most commonly evaluated by the transfer-length method (TLM), in which the total resistance of devices with different channel lengths is measured at a fixed gate bias. A linear fit to $R_{total} = 2R_c + R_{sh}(L/W)$ gives twice the contact resistance from the intercept and the channel sheet resistance from the slope. Four-probe measurements provide an independent way to exclude voltage drops at the contacts. For meaningful comparison, R_c should be normalised by contact width and reported at matched carrier density, gate bias and temperature, because it is strongly bias dependent [2, 8].

3.3. Gate dielectrics and flexible substrates

The gate dielectric controls electrostatic coupling, leakage current, operating voltage and interface trap density. High-permittivity materials such as Al_2O_3 and HfO_2 can provide strong gate control at reduced voltage. Nevertheless, the chemically inert surface of a TMD does not provide favourable nucleation sites for conventional atomic layer deposition. Surface treatments can improve dielectric coverage, but they may also introduce defects and reduce carrier mobility.

Van der Waals integration offers an alternative route in which a dielectric is prepared separately and subsequently transferred onto the TMD. Lu et al. demonstrated the wafer-scale integration of ultrathin high-κ dielectrics with two-dimensional circuits through a dry-transfer process [10]. The method reduced direct damage to the semiconductor and enabled functional logic circuits. However, transferring an additional layer increases process complexity, and the mechanical durability of the dielectric and its interfaces remains important for flexible operation.

The substrate must also be treated as an active component of the device rather than an inert support. Polyimide offers relatively high thermal stability, whereas transparent PET and PEN substrates generally impose stricter processing-temperature limits. Substrate thickness and modulus affect strain transfer during bending, while surface roughness can alter the quality of the TMD and dielectric interfaces. Encapsulation can protect the channel from moisture and adsorbates, but it also changes the neutral mechanical plane and the overall stiffness of the device. The position of the neutral mechanical plane depends on the thickness and elastic modulus of the constituent layers. Consequently, successful flexible TMD transistors require co-design of the semiconductor, contacts, dielectric, substrate and encapsulation instead of independent optimisation of each layer.

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4. Progress from individual devices to flexible circuits

4.1. Development of flexible TMD transistors

The following case studies are evaluated across four linked dimensions: electrical performance, including on-current, switching ratio and operating voltage, scalability, including channel length, device area and process uniformity, circuit-level functionality, including transistor count and logic complexity, and mechanical reliability, including bending strain, cycle number and retention of electrical characteristics. Considering these dimensions together prevents a record value in one device from being treated as evidence of overall technological maturity [2, 6, 8]. Early flexible TMD research largely focused on demonstrating that atomically thin semiconductors could maintain transistor behaviour under bending. Subsequent work has increasingly addressed shorter channel lengths, large-area material growth, lower operating voltage and circuit integration. This development represents a transition from proof-of-concept devices towards functional electronic systems, although progress at each level has not occurred at the same rate.

Daus et al. demonstrated flexible transistors based on MoS_2, $MoSe_2$ and WSe_2 with nanoscale features [3]. Their MoS_2 devices achieved channel lengths down to approximately 60 nm and high on-state current, showing that flexible transistors can benefit from device scaling rather than remaining limited to micrometre-scale channels. The simultaneous transfer of the TMD and pre-patterned contacts also reduced the need for high-resolution processing directly on the flexible substrate. However, this result primarily demonstrated the performance potential of carefully fabricated individual devices. It did not by itself resolve the challenges of wafer-scale uniformity, circuit yield or long-term cyclic reliability.

Large-area fabrication has provided an important route towards greater integration. Li et al. produced flexible and transparent electronics using wafer-scale monolayer MoS_2, demonstrating transistor arrays and basic circuits with high current on/off ratios [11]. Tang et al. subsequently combined wafer-scale monolayer MoS_2 with an ultrathin high-κ gate stack to develop low-power flexible integrated circuits [4]. These studies indicate that the performance of flexible TMD electronics depends on the combined optimisation of semiconductor quality, dielectric thickness, contact design and process uniformity rather than the channel material alone.

A further increase in circuit complexity was reported by Peng et al. [5]. Flexible MoS_2 transistors were integrated into combinational and sequential logic elements, including NAND and XOR gates, a half-adder, a latch and a clock-division module containing 112 transistors. This work represents a significant step beyond simple inverters and ring oscillators because it demonstrates higher-level system functionality within the same flexible platform.

4.2. Critical comparison of reported progress

Despite these advances, comparisons based only on the highest mobility, current density or smallest channel length can be misleading. Reported values depend on contact resistance, dielectric capacitance, channel geometry and the method used to extract mobility. Furthermore, a single high-performing device provides limited information about process reproducibility. For circuit applications, device-to-device variation, functional yield, threshold-voltage distribution and stability under repeated deformation can be more important than the maximum performance achieved by an individual transistor.

The 112-transistor circuit reported by Peng et al. demonstrates growing integration capability, but its scale remains far below that of mature silicon electronics [5]. Most flexible MoS_2 circuits also

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rely predominantly on n-type transistors, which restricts the development of balanced complementary logic [2, 5, 8, 11]. Current evidence therefore supports TMDs as promising materials for specialised low-power, transparent and mechanically conformable systems, rather than as immediate replacements for conventional silicon integrated circuits.

5. Remaining challenges and future directions

5.1. Material uniformity and device yield

Large-area uniformity remains one of the main barriers to practical flexible TMD electronics. Variations in grain orientation, point-defect concentration, layer thickness and transfer-induced contamination can produce substantial differences in mobility, threshold voltage and off-state current. These variations become increasingly important as the number of transistors in a circuit increases because the failure of a small proportion of devices can prevent the entire circuit from operating correctly. Future studies should therefore report performance distributions and functional yield across complete wafers rather than selecting only the best-performing devices. Defect passivation and healing provide a promising approach. Kumral et al. demonstrated that treating defects in monolayer MoS_2 could improve both electronic uniformity and mechanical reliability, indicating that defect engineering may address multiple limitations simultaneously [12].

5.2. Mechanical and environmental reliability

Flexible TMD transistors retain their electrical characteristics after bending but the testing conditions used by different studies vary. Bending radius alone is insufficient because the strain experienced by the channel also depends on substrate thickness, layer position and device geometry. The number of cycles, bending direction and electrical measurement conditions must also be considered. Cui et al. showed that monolayer MoS_2 and WSe_2 can display significant variations in fracture strength and fatigue lifetime, demonstrating the need for statistical mechanical testing [7].

Future reliability protocols should report calculated channel strain, performance retention and failure mode after repeated loading. Testing should also combine mechanical deformation with temperature, humidity and prolonged electrical bias because flexible devices used on the human body or outdoors will experience several forms of loading simultaneously. Particular attention should be paid to dielectric cracking, metal fatigue and interface delamination, since these components may fail before the TMD channel.

5.3. Complementary logic and scalable manufacturing

Most large-area MoS_2 transistors show n-type behaviour, while reproducible p-type devices remain less developed. This imbalance restricts the fabrication of complementary logic, which is required to reduce static power consumption and improve noise margins. WSe_2 and contact-engineered TMDs offer possible p-type channels, but their polarity and threshold voltage must remain stable during fabrication and bending [2, 8, 11].

Scalable manufacturing will also require low-temperature growth, clean transfer, uniform high-κ dielectrics and contacts that combine low resistance with mechanical durability. These requirements should be optimised as an integrated process rather than as separate record-performance demonstrations. In the near term, TMDs are more likely to complement conventional silicon in specialised applications, including transparent sensors, wearable health monitors and conformable

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low-power circuits. Progress should consequently be judged by reproducibility, reliability and system-level function rather than by isolated improvements in mobility or current density.

6. Conclusion

Two-dimensional transition metal dichalcogenides (TMDs)—including MoS_2, WS_2, and WSe_2—offer a compelling platform for flexible transistors: their atomic thickness, finite bandgaps, and strong gate electrostatics enable low-power, transparent, and conformable electronics. Critically, their ultrathin channels minimize bending-induced strain, and they retain semiconducting behavior even in mechanically compliant structures. Yet transistor performance depends on the full multilayer stack—not just the TMD channel. Significant progress has been made—from single proof-of-concept devices to nanoscale transistors, wafer-scale arrays, and functional integrated circuits. Low-power MoS_2 circuits and medium-scale systems (>100 transistors) demonstrate growing functional complexity. However, these advances do not yet reflect a manufacturable technology: high mobility or short channel length cannot offset poor uniformity, low functional yield, or inadequate reliability validation.

Key bottlenecks lie in material defects, transfer-induced contamination, contact resistance, dielectric integration, and device-to-device variability. Mechanical robustness must be evaluated at the system level—metal electrode cracking, dielectric degradation, and interface delamination often precede TMD channel failure. Thus, interface engineering is essential to preserve both electrical performance and mechanical integrity. Meaningful cross-study comparison requires standardized testing: quantified strain, cyclic bending, environmental stress, and statistical sampling across device populations.

Future success hinges on integrated materials-and-process development—specifically: defect-controlled wafer-scale TMD growth; clean, low-damage transfer; mechanically resilient interfaces; ultrathin high-κ dielectrics; and stable p-type devices for complementary logic. TMD transistors will not displace silicon in the near term. Instead, their niche lies in applications demanding extreme thinness, transparency, or mechanical conformity—where they complement, rather than replace, silicon. Ultimately, the shift from record-breaking devices to reproducible, reliable, and scalable systems will define the real-world impact of flexible TMD electronics.

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