



Research Paper

Effect of oxide buffer layers on the tribological properties of PtSe2/oxide heterostructures in different environment conditions

Submission ID 925964ee-be50-41b9-a649-4f50259102de

Submission Version Initial Submission

PDF Generation 11 Sep 2026 12:46:59 EST by Atypon ReX

Authors

Dr. Andrii Kozak
Corresponding Author
Submitting Author

 [ORCID](https://orcid.org/0000-0003-4226-8737)
<https://orcid.org/0000-0003-4226-8737>

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Michaela Sojková

 [ORCID](https://orcid.org/0000-0002-7490-3240)
<https://orcid.org/0000-0002-7490-3240>

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Boris Hudec

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Igor Píš

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Jana Hrdá

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Martin Hulman

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Edmund Dobročka

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Peter Nádaždy

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

Dr. Milan Ćapajna

Affiliations

- Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

 ORCID

<https://orcid.org/0000-0003-1099-2050>

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Effect of oxide buffer layers on the tribological properties of PtSe₂/oxide heterostructures in different environment conditions

Andrii Kozak*, Michaela Sojková, Boris Hudec, Igor Piš, Jana Hrdá, Martin Hulman, Edmund Dobročka, Peter Nádaždy, Milan Ťapajna*

Institute of Electrical Engineering, Slovak Academy of Sciences, Dúbravská cesta 9, 841 04 Bratislava, Slovakia

*andrii.kozak@savba.sk; michaela.sojkova@savba.sk; boris.hudec@savba.sk; igor.pis@savba.sk; jana.hrda@savba.sk; martin.hulman@savba.sk; edmund.dobrocka@savba.sk; peter.nadazdy@savba.sk; *milan.tapajna@savba.sk

Although ultrathin van der Waals layers exhibit superior sliding properties for solid lubrication, their ultrathin nature renders them prone to rapid wear. To address this challenge, this work investigates PtSe₂ thin films as environment-adaptive solid lubricants. We evaluate the influence of different oxide buffer layers (Al₂O₃, HfO₂, and TiO₂) grown by atomic layer deposition (ALD) on the structural, chemical, and tribological properties of PtSe₂ films on Si and stainless steel (16MnCr5) substrates. The tribological behavior was evaluated in ambient air and vacuum conditions by ball-on-disc test with Si₃N₄ counterpart. On Si substrates, PtSe₂/TiO₂ exhibited transfer-film-driven sliding in both air (COF~0.18) and vacuum (COF~0.33). Meanwhile, PtSe₂/Al₂O₃ degraded rapidly in air but achieved a low COF of 0.08 in vacuum due to localized PtSe₂ inclusions. Finally, PtSe₂/HfO₂ demonstrated superior interfacial stability and film retention in both environments. Integration of the PtSe₂/HfO₂ onto 16MnCr5 yielded similar COF values during the initial wear stages but exhibited contrasting environment-dependent durability. While ambient air led to early failure with a COF ~0.3, vacuum testing resulted in a substantial extension of wear life exceeding 10000 cycles with a drop in COF to ~0.2. Structural

and chemical characterizations confirmed that PtSe₂ remains intact throughout sliding, while the HfO₂ buffer layer prevents its removal from the wear track. These findings demonstrate that tailoring interfacial bonding via ALD buffer layers offers an effective strategy for developing PtSe₂ as a lubricant suitable for variable environmental conditions, such as space applications or MEMS devices.

Keywords: friction in vacuum, 2D materials, buffer layer, PtSe₂, ALD

1. Introduction

The development of solid lubricants engineered for reliable performance across diverse environments is critical for modern aerospace, automotive, and micro-electromechanical systems (MEMS). Among solid-state materials, two-dimensional (2D) van der Waals (vdW) materials including transition metal dichalcogenides (TMDs), graphene derivatives, and MXenes have emerged as the most promising candidates for lubrication at the micro- and nanoscale and under extreme conditions [1–8]. This is primarily due to their layered crystal structures, in which strong intra-layer covalent bonds confer high in-plane mechanical strength, while weak interlayer vdW forces yield low shear strength during sliding [5–7]. In these systems, atomic-scale stick-slip motion and lattice incommensurability govern solid-state lubricity [9,10].

Among 2D materials, TMDs have demonstrated the most promising tribological properties, including superlubricity and high wear resistance [10,11]. However, the practical application of 2D-material-based solid lubricant is often limited by environmental sensitivity, because atmospheric moisture and oxygen increase interlayer shear resistance and promote rapid oxidation [11–14]. These limitations can be partially overcome by synthesizing highly ordered films [15], or by doping MoS₂ with non-metallic (C, O, N, P, B) or metallic (Ti, Cr, Ni, Zr, Nb, Pb, Au) elements [16]. The environmental limitations are effectively mitigated in the composite

films. For instance, $\text{MoS}_2/\text{a-C:Si}$ composites maintain low COF at about 0.051 and 0.018 in high-temperature air and vacuum, respectively, due to improved thermal stability and interfacial carbon precipitation [17].

Beyond composite engineering, chemical substitution within the TMD lattice offers another route toward environmental adaptability. TMDs, in which the chalcogen atom is Se or Te, preserve low friction at elevated temperatures up to 450 °C [18]. Moreover, transition-metal diselenides (such as MoSe_2 and WSe_2) exhibit lower environmental sensitivity compared to disulfides (such as MoS_2 and WS_2) [5] [19]. For instance, WSe_2 films have been reported to achieve nearly identical, low COF values of 0.058 in vacuum and 0.056 in ambient air [5]. Although conventional TMD coatings (MoS_2 , WS_2 , MoSe_2 , and WSe_2) have been extensively investigated, noble-metal TMD coatings in which the transition metal is Pt or Pd have been studied primarily at the nanoscale [20–23]. Nonetheless, recent studies on PtSe_2 coatings demonstrate that they offer high resistance to atmospheric humidity alongside thermal stability up to 400 °C, making them promising materials for environment-adaptive lubricants [24–26].

Despite the excellent lubricity and stability of 2D TMDs, their practical performance is often limited by poor interfacial adhesion, delamination, and coating failure [27–31]. Synthesizing TMD films on engineering substrates requires surface modification, such as thin buffer layers, surface patterning, or pre-treatments [32,33]. For this purpose, atomic layer deposition (ALD) offers uniquely uniform coverage and exceptional conformality, making it widely used for surface protection and advanced electronics [34]. Metal oxides are the most commonly grown ALD materials, where water vapor generates reactive surface hydroxyl (–OH) groups that readily bond with chemisorbed organometallic precursors [35], in a discrete, substrate-limited reactions, repeated through a desired number of ALD cycles. In surface engineering, ALD buffer layers prevent substrate interdiffusion, eliminate surface defects and dangling bonds, and allow

tailoring the morphology and structure of the subsequently grown coating [36–38]. In the case of PtSe₂, ALD buffer layers also prevent unwanted chemical reaction between selenium gas and the substrate [38]. However, the impact of oxide buffer layers (OBS) on overall properties of TMDS layers remains unexplored.

In this work, we systematically investigate the synthesis, structural characteristics, and environmental tribological behavior of PtSe₂ thin films grown on three different ALD-grown OBL: amorphous aluminum oxide (Al₂O₃), polycrystalline hafnium oxide (HfO₂), and polycrystalline anatase titanium dioxide (TiO₂). These heterostructures were deposited on Si and steel (16MnCr5) substrates and evaluated using ball-on-disc measurements under both ambient air and vacuum conditions. Our comprehensive structural, chemical, and surface characterization reveals that the choice of OBL controls interfacial stability and the resulting friction mechanisms. Specifically, TiO₂ promotes transfer-film-driven sliding, Al₂O₃ enables inclusion-mediated lubrication in vacuum, and HfO₂ provides superior interfacial bonding that prevents coating delamination. This study demonstrates the importance of interfacial oxide engineering for TMDs film adhesion and highlights the strong potential of PtSe₂/oxide heterostructures as advanced tribological coatings for MEMS and automotive applications.

2. Materials and Methods

2.1. Oxide buffer layers and PtSe₂ fabrication

PtSe₂/oxide heterostructures were prepared on two types of substrates: (i) single-crystal Si wafers (10 × 10 mm size) with native SiO₂ surface layer and (ii) 16MnCr5 steel substrates (16 mm in diameter), using the same deposition parameters. To prepare heterostructures, first, three different types of oxides: Al₂O₃, HfO₂, and TiO₂, were individually deposited using Beneq TFS200 ALD equipment at growth temperature of 250°C. Trimethylaluminum, tetrakis(ethylmethyldamido)hafnium, and titanium tetraisopropoxide were used as the metal

precursors for Al_2O_3 , HfO_2 , and TiO_2 , respectively, while water was used as the oxygen reactant. The number of ALD cycles was 300 for Al_2O_3 , 390 for HfO_2 , and 820 for TiO_2 , targeting a nominal film thickness of ~ 30 nm for each OBL. Following ALD oxide deposition, PtSe_2 films were fabricated on top of the OBL via a two-step thermally-assisted conversion (TAC) method [39]. A thin platinum film with a thickness of 3 nm was first deposited onto the oxide-buffered substrates via DC magnetron sputtering. The deposition was conducted using a Pt target in Ar atmosphere (10^{-3} mbar) at room temperature. The pre-deposited Pt films were subsequently selenized in a custom-built, single-zone chemical vapor deposition system. Both the Pt-coated substrate and elemental Se powder were placed at the center of the furnace tube and heated to a reaction temperature of 400 °C in N_2 atmosphere at ambient pressure. These TAC processing conditions yielded a PtSe_2 film with an average thickness of ~ 14 nm [23].

2.2. Structural, chemical, and surface characterization

The structural, microstructural, and surface properties of the synthesized oxide layers and PtSe_2 /oxide heterostructures were comprehensively characterized using a set of analytical techniques. The thickness of the pre-deposited oxide layers was determined using spectroscopic ellipsometry (SENTECH). Surface topography was investigated by an atomic force microscope (AFM) MultiMode 8 (Bruker, USA). To achieve high-quality surface mapping, AFM measurements were performed using probes with a nominal tip radius of 2 nm (ScanAsyst, Bruker). Raman spectroscopy was performed to investigate the structural properties of the samples using a WITec Alpha 300R microscope (Germany) equipped with a 532 nm excitation laser. The laser power was set to 0.5 mW. X-ray diffraction (XRD) measurements were collected to evaluate the crystal structure of the deposited films using a Bruker D8 DISCOVER diffractometer equipped with a 12-kW rotating anode $\text{Cu-K}\alpha$ radiation source. The surface elemental composition and chemical bonding states were analyzed by X-ray Photoelectron

Spectroscopy (XPS) with a Thermo Scientific Nexsa G2 Surface Analysis System (Thermo Fisher Scientific, UK). The system used a micro-focused, monochromatic Al K α X-ray source (1486.68 eV). The beam size was set to 50 μ m. Spectra were acquired in constant analyzer energy mode at a pass energy of 50 eV with a total energy resolution of 0.6 eV in the normal-emission geometry. Energy scale calibration was performed using the internal Au, Ag, and Cu standards. No charging compensation was required for the films deposited on the steel substrate. For oxide buffer layers deposited on silicon, a dual-beam charge-compensation system was implemented to mitigate sample charging. For the oxide samples, binding energies were referenced to the C 1s peak of adventitious carbon (284.8 eV). The XPS spectra were fitted with the KherveFitting open-source software [40] using Voigt functions after subtracting a Shirley background. The Pt 4f spectra were fitted with asymmetric Gaussian convoluted Doniach–Sunjic line shapes. The Fe 3p peak from the steel substrate was modeled using an asymmetric Lorentzian function [39], with the asymmetry and width parameters determined from the Fe 3p spectrum measured on a Fe reference sample under the same system setup. Relative atomic concentrations were determined from peak areas and relative sensitivity factors provided in the Advantage software package (Thermo Scientific).

2.3 Tribological analysis

The tribological performance of the heterostructures was evaluated using an Anton Paar TRBV tribometer operated in a reciprocating configuration. A silicon nitride (Si₃N₄) ball with a diameter of 6.3 mm was selected as the sliding counterbody. All tribological tests were conducted under a constant applied normal load of 0.5 N at a sliding velocity of 0.5 cm/s. To evaluate the impact of environmental conditions on the friction and wear mechanisms, tests were systematically performed under ambient air and vacuum ($1 \pm 0.2 \times 10^{-5}$ mbar) conditions.

Following the friction tests, the resulting wear tracks were analyzed using AFM, Raman spectroscopy, optical profilometry, Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM/EDX), and XPS. Surface morphology and elemental mapping across the wear tracks were examined using a Quanta FEG-250 Schottky field-emission microscope. Additionally, ball surface topographies and wear track depth profiles were evaluated using a 3D optical profilometer (ContourX-500, Bruker, USA).

3. Results and discussion

3.1. Structure and topography of oxide buffer layers

The as-deposited ALD oxides (Al_2O_3 , HfO_2 , and TiO_2) on Si substrates were first investigated by AFM (Figures 1a–c), Raman spectroscopy (Figure 1d) and XRD (Figure 1e). AFM images demonstrated a relatively low root-mean-square surface roughness (R_{RMS}) of 0.3 nm for Al_2O_3 , compared to significantly higher values of 2.3 nm and 1.8 nm for HfO_2 and TiO_2 , respectively (Table 1). The smooth surface topographies of Al_2O_3 films suggest their amorphous nature, whereas HfO_2 is characterized by fine nanoscale surface features, and TiO_2 displays a polycrystalline surface morphology. These observations were confirmed by Raman and XRD analysis. Raman spectra (Figure 1d) revealed characteristic vibrational modes peaks for the TiO_2 samples, while no Raman active modes were detected for the Al_2O_3 and HfO_2 layers. In fact, thin layers of HfO_2 are frequently Raman-inactive [41–42]. Further XRD characterization (Figure 1e) confirmed the amorphous nature of the Al_2O_3 layer and revealed a weak diffraction signal from HfO_2 , along with more intense peaks from TiO_2 , indicating their respective crystalline structures.

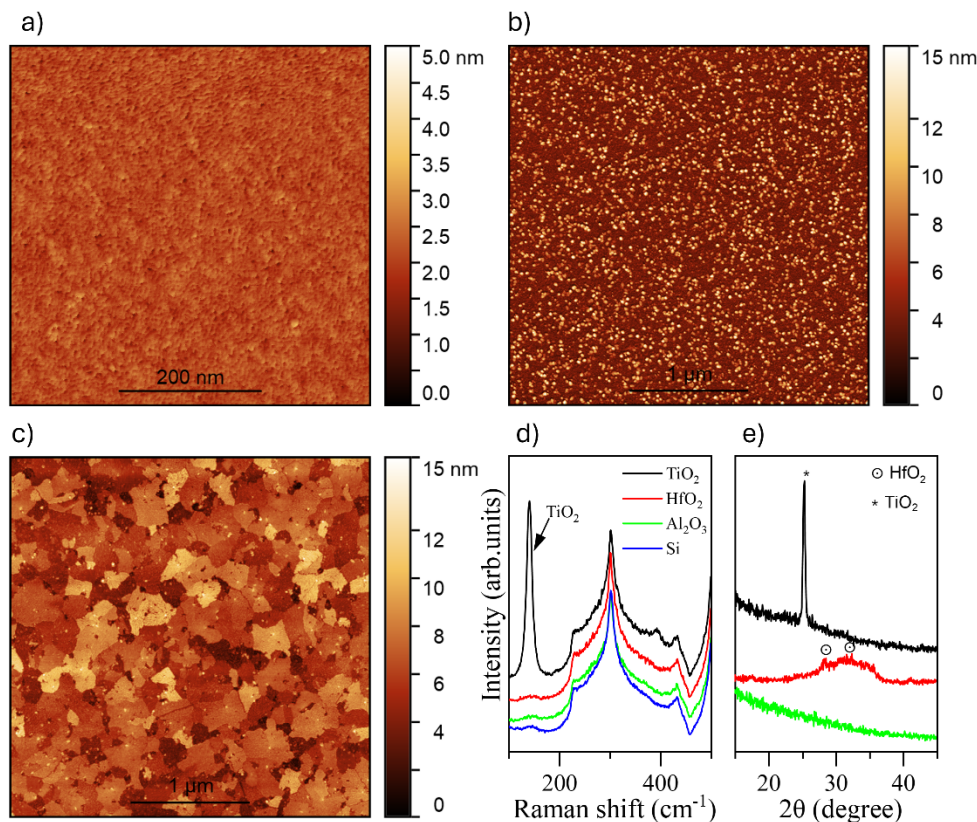


Figure 1. AFM images of as-deposited Al_2O_3 (a), HfO_2 (b), and TiO_2 (c) oxides on Si substrates. Corresponding Raman spectra (d) and XRD pattern (e) of the as-deposited oxides.

Table 1. R_{RMS} of the as-deposited ALD OBL and top PtSe_2 films, along with the average crystallite domain size of the PtSe_2 films measured by AFM.

Substrate / OBL	R_{RMS} of OBL (nm)	R_{RMS} of PtSe_2 (nm)	PtSe_2 crystallite size (nm)
Si/ Al_2O_3	0.3	1.7	8.6
Si/ HfO_2	2.3	1.9	12.5
Si/ TiO_2	1.8	1.7	11.5
Si/-/-	0.1	1.2 (1.0*)	11.1(7.1*)

* - Crystallite size and R_{RMS} values estimated by excluding large irregular features.

XPS analysis further confirmed the successful growth and near-stoichiometric elemental composition of all ALD films (Figure 2 and Table 2).

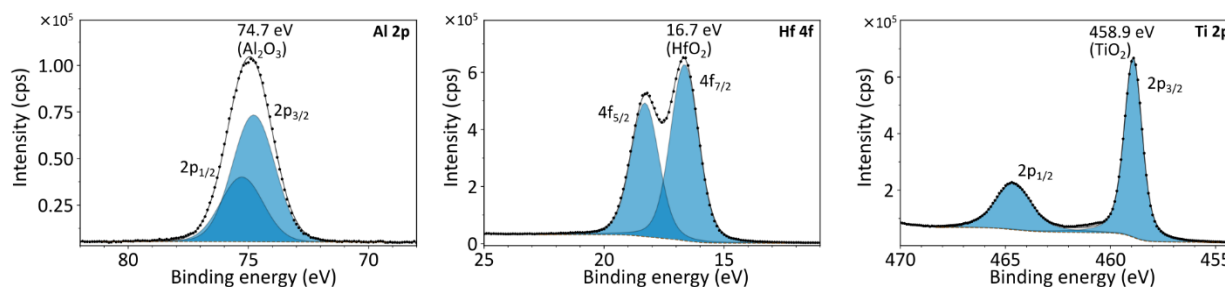


Figure 2. Al 2p, Hf 4f, and Ti 2p core-level XPS spectra of the as-deposited ALD Al₂O₃, HfO₂, and TiO₂ layers on Si substrates.

Table 2. Apparent atomic concentrations for the buffer layers determined by XPS.

OBL	Main components concentration (at.%)
Al ₂ O ₃	Al – 31.6; O – 48.4; C – 20.0
HfO ₂	Hf – 22.3; O ²⁻ – 41.5; O(-OH) – 10.8; C – 25.3
TiO ₂	Ti – 24.5; O ²⁻ – 45.6; O(-OH) – 21.1; C – 8.7

Increased R_{RMS} of HfO₂ and TiO₂ is primarily due to a higher density of nanoscale step edges and oxide grain boundaries. These morphological effects could promote localized surface oxidation and moisture adsorption, thereby increasing the concentration of hydroxyl (–OH) group components in the films observed in XPS [43]. The oxide phase composition is also known to affect the surface free energy [43], which can subsequently modulate the interfacial adhesion at neighboring interfaces [44] (e.g. bonding with the underlying substrate or the overlying PtSe₂ layer).

3.2. Structure and topography of PtSe₂ layers

Topographical analysis of the samples after PtSe₂ conversion (Figures 3a–d) showed comparable surface roughness across all heterostructures, with R_{RMS} in the range of 1.5 - 1.9 nm (Table 1). Furthermore, AFM measurements show that the average PtSe₂ grain size ranged from 8.6 nm on the Al₂O₃ OBL to 12.5 nm on the bare HfO₂ OBL (Table 1).

Raman and XPS spectroscopies (Figure 4) were used to verify the growth of PtSe₂. Raman, in particular, demonstrate peaks corresponding to the characteristic E_g and A_{1g} vibrational modes of PtSe₂ [23]. The sample composition was confirmed by XPS analysis of the Pt 4f and Se 3d core levels (Figure 4). The Pt 4f_{7/2} and Se 3d_{5/2} peak maxima, measured at 73.0 ± 0.1 and 54.4 ± 0.1 eV, respectively, together with the Se:Pt stoichiometry of 2.0 ± 0.2 , determined from the integrated areas of the Pt-Se related components of the Se 3d and Pt 4f spectra, confirm the formation of near-stoichiometric PtSe₂ [39]. In addition to PtSe₂, a weak signal corresponding to off-stoichiometric Pt_xSe_y with a Pt4f_{7/2} peak at 72.0 ± 0.1 eV was detected in the Pt 4f spectrum, while the Se 3d core level displayed additional doublets with Se 3d_{5/2} peaks at 55.2 and 58.0 eV, attributed to elemental Se [45] and oxidized Se species [46], respectively. Overall, the XPS measurements confirmed stoichiometric PtSe₂ bonding with negligible surface oxidation, demonstrating remarkably high film quality despite the varying oxide chemistry and the relatively low synthesis temperature compared to benchmark PtSe₂ layers reported previously [39].

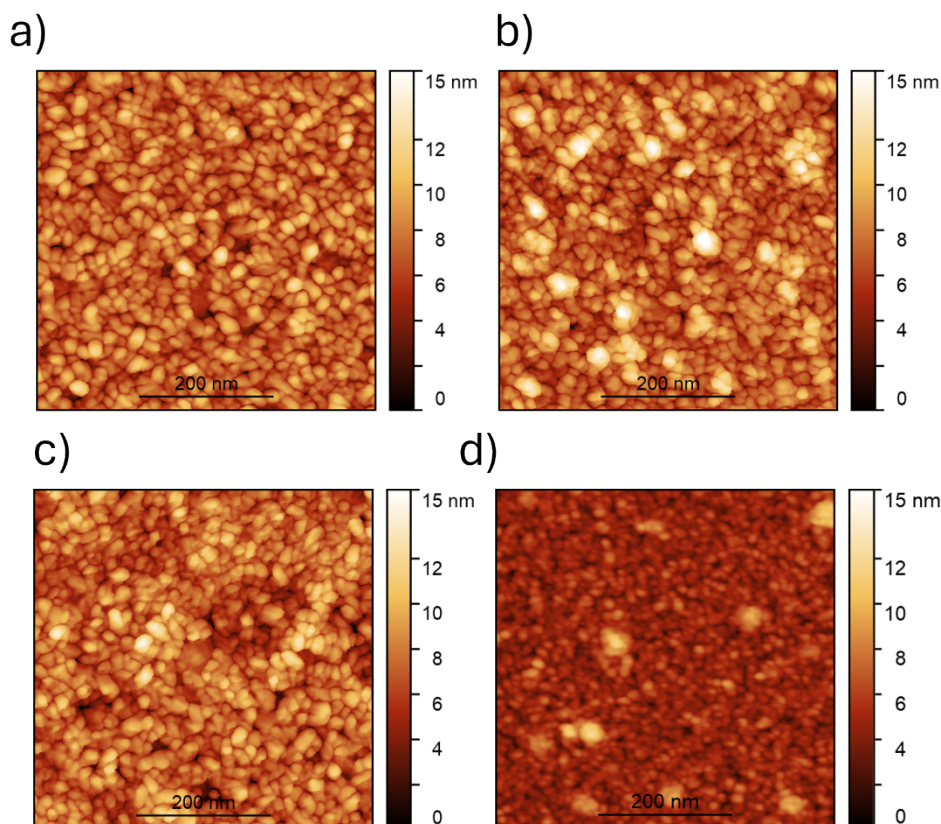


Figure 3. AFM topographical images of PtSe₂ layers synthesized on different ALD buffer layers: (a) Al₂O₃, (b) HfO₂, (c) TiO₂, and (d) PtSe₂ on a reference Si substrate.

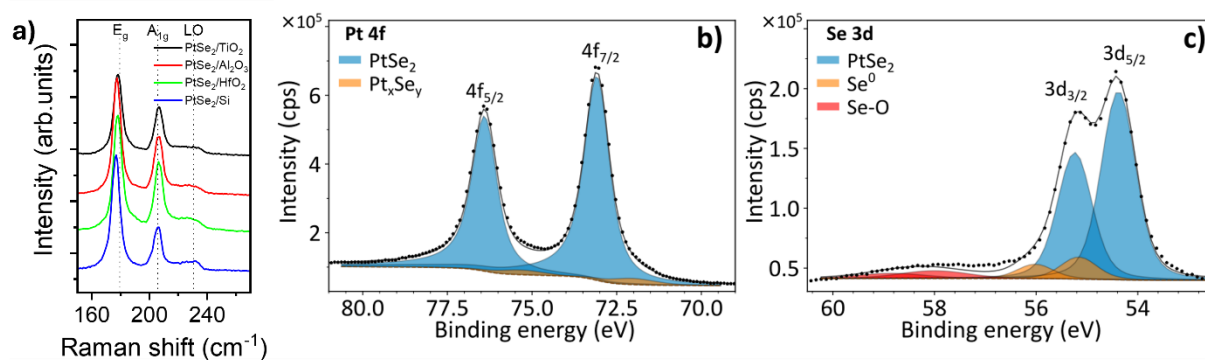


Figure 4. (a) Raman spectra of the PtSe₂ layers synthesized on Al₂O₃, HfO₂, and TiO₂ ALD buffer layers compared to a reference PtSe₂ film grown on Si. Deconvolution of XPS (b) Pt 4f and (c) Se 3d core level spectra of the PtSe₂ grown on the HfO₂ buffer layer.

In previous study, *in situ* grazing-incidence wide-angle x-ray scattering of TAC PtSe₂ on sapphire suggests that high-temperature processes promote horizontally aligned epitaxial layers, affected by lattice mismatch and interfacial strain [47]. In contrast, vdW substrates such as mica could provide an atomically flat, inert surface that facilitates strain-free planar growth for layered crystals, whereas Si substrates exhibit active surface states that prevent epitaxial alignment [48]. In turn, the ultra-smooth Al₂O₃ and Si surfaces enable uniform solid-state conversion during TAC, yielding random rotational orientations [48], while, a high density of nucleation centers prevents subsequent flake merging, resulting in the smallest average PtSe₂ grain sizes (7.1–8.6 nm). Vice versa, the higher surface roughness, grain edges, and nanoscale valleys of HfO₂ and TiO₂ can act as barriers that suppress planar lateral expansion [48]. TAC occurring around these defect sites could force the out-of-plane rotation of neighboring domains, leading to their localized clustering and merging. This reorientation and localized clustering ultimately yield larger observed inclusions and grain sizes (11.5–12.5 nm) on HfO₂ and TiO₂, which may affect their environment-dependent sliding properties [49].

3.3. Tribological properties of PtSe₂ thin films with ALD buffer layers on Si substrates

To investigate the influence of ALD OBL on the tribological behavior of PtSe₂, the friction tests were conducted on both the PtSe₂/oxide heterostructures as well as on the standalone oxides deposited on Si substrates. Testing of all oxides in ambient resulted in their rapid degradation, eventually reaching COF characteristic of the uncoated Si (Figure 5). Under vacuum conditions, the uncoated Al₂O₃ layer similarly failed within the first few cycles, reaching a COF of 0.2 with friction spikes up to 0.7 (reproducing the behavior of the Si substrate). In contrast, the uncoated HfO₂ and TiO₂ layers exhibited extended tribological durability over 1000 cycles with COFs of 0.7 and 0.6, respectively.

Overall, coating the ALD oxide buffer layers with PtSe₂ improved tribological performance (Figure 5). In particular, in ambient air, PtSe₂/HfO₂ and PtSe₂/TiO₂ maintained stable COFs of ~0.13 and ~0.18, respectively, for over 600 cycles, whereas PtSe₂/Al₂O₃ failed within 130 cycles with a COF of ~0.30 (Figure 5). Under vacuum, PtSe₂/Al₂O₃ showed a sharp reduction in COF to 0.08, maintaining over ~750 cycles, while the PtSe₂/HfO₂ and PtSe₂/TiO₂ demonstrated significantly higher COFs of 0.65 and 0.33 over ~1000 cycles, respectively. To gain insight into underlying sliding mechanisms, friction tests were interrupted during the low-COF stage, and resulting wear tracks were then analyzed using optical profilometry (Figure 5, insets), AFM, and Raman spectroscopy (Figure 6).

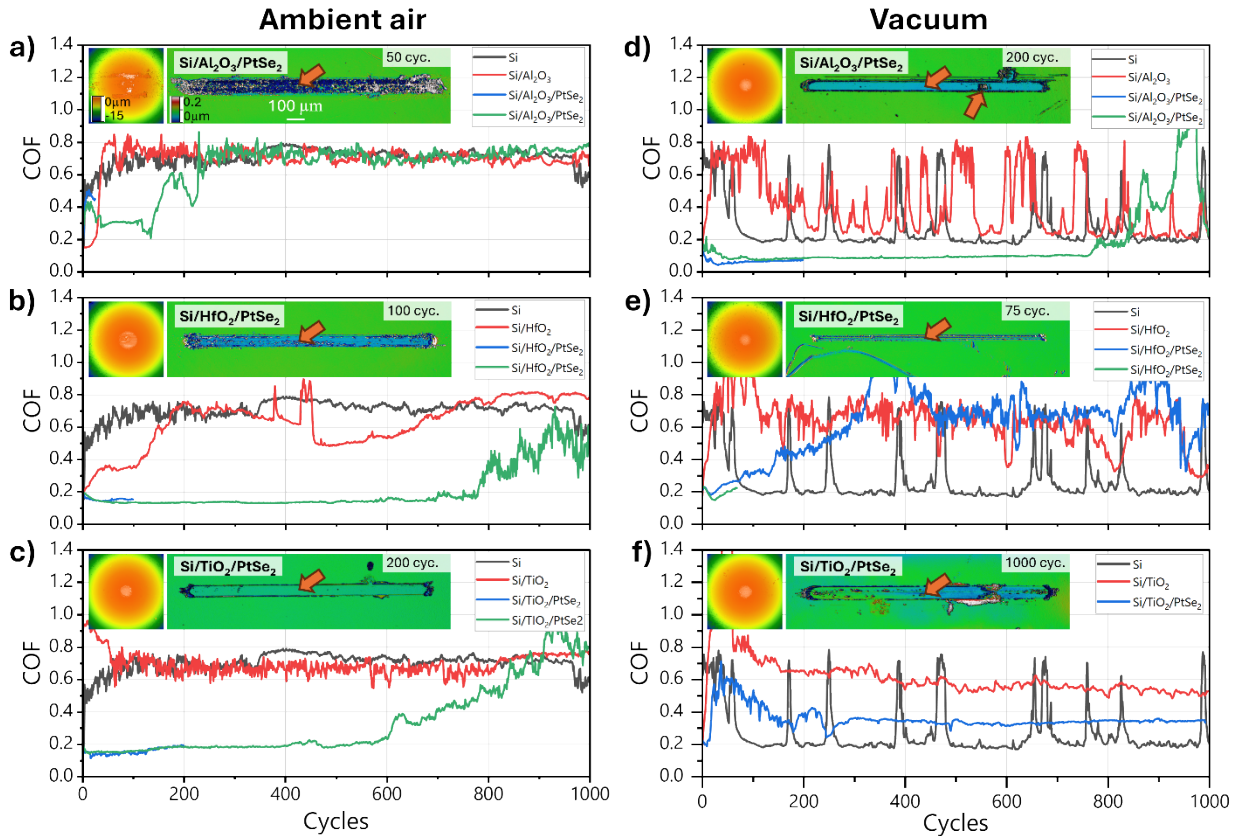


Figure 5. COF as a function of sliding cycles for PtSe₂ films synthesized on Al₂O₃, HfO₂, and TiO₂ oxides and bare ALD oxides under (a–c) ambient air and (d–f) vacuum environments.

Corresponding optical profilometry images of the sliding counterbody balls and wear tracks, taken after the interruption of the test in the low-COF stage, are shown as insets in each figure.

Arrows mark AFM and Raman analysis positions.

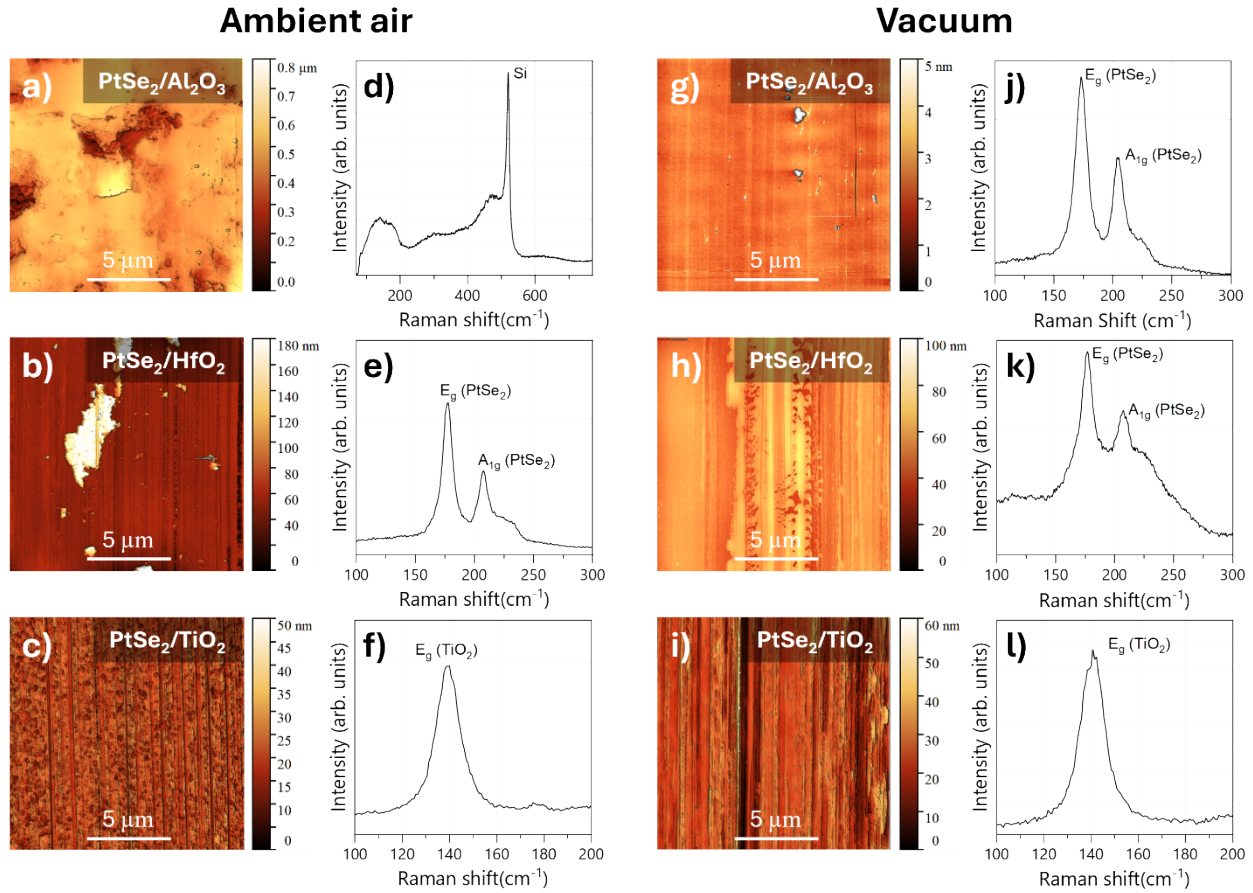


Figure 6. Wear track AFM topography (a–c, g–i) and corresponding Raman spectra (d–f, j–l) for PtSe₂ heterostructures tested in ambient air (a–f) and vacuum (g–l). (a, d, g, j) – PtSe₂/Al₂O₃, (b, e, h, k) – PtSe₂/HfO₂, and (c, f, i, l) – PtSe₂/TiO₂ heterostructures. Raman spectra in Figure 6j are taken from the largest residual particles within the wear track (Figure 5 d).

Analysis of the samples tested in ambient air showed that PtSe₂/Al₂O₃ heterostructures suffered adhesive wear as confirmed by AFM (Figure 6a). Both, PtSe₂/HfO₂ and PtSe₂/TiO₂ heterostructures demonstrate adhesive delamination and transfer film onto the counterbody ball

(Figure 5 b, c, e, f, insets). However, these heterostructures demonstrated different wear track topography and structural properties (Figures 6 b, c, e, f). In particular, PtSe₂/HfO₂ heterostructure retained residual PtSe₂ within the middle of the wear track, whereas the PtSe₂/TiO₂ heterostructure underwent complete removal of the PtSe₂ film, exposing only TiO₂. Under vacuum conditions, residual PtSe₂ was observed in wear tracks of both, PtSe₂/Al₂O₃ (as small inclusions) and PtSe₂/HfO₂ (across the entire track surface) heterostructures (Figures 6g–h, 6j–k). In contrast, it was completely absent in the PtSe₂/TiO₂ heterostructures (Figures 6i, 6l). Counterbody ball analysis in vacuum (Figure 5) showed no transfer layer for Al₂O₃ and HfO₂, but its appearance was observed for TiO₂.

The COF, structural, and surface analyses demonstrate the different environment-dependent tribological mechanisms for each heterostructure. For the PtSe₂/Al₂O₃ heterostructure under vacuum, small PtSe₂ inclusions formed within the wear track effectively protected the Al₂O₃ layer from wear, enabling a low COF of 0.08, similar to MoSe₂ tribolayer in sliding interface in Mo-Se-C coatings [50]. Conversely, for PtSe₂/HfO₂ heterostructure, strong oxide adhesion prevents eventual coating wear and retains PtSe₂ throughout the wear track. This interfacial bonding results in a gradual increase in COF to 0.65 in vacuum, while supporting a low, stable COF of 0.13 in ambient air, followed by gradual failure. Similar friction behavior for PtSe₂/HfO₂ heterostructure in both testing environments can indicate continuous abrasive coating removal [51], while steady-state friction is primarily caused by wear-track morphology and the chemical nature of the interface [52]. Finally, the PtSe₂/TiO₂ heterostructure behaved similarly in vacuum and in ambient air, where sliding friction was primarily governed by the contact interface between the transferred PtSe₂ film on the ball and the exposed TiO₂ OBL, consistent with transfer-film-driven sliding mechanisms reported for WC/a-C solid-lubricant systems [53]. The formation of a transfer film on the counterbody ball for PtSe₂/TiO₂ heterostructure can be

attributed to weaker bonding to a rough, polycrystalline surface. In particular, grain boundaries and surface facets of these TiO_2 grains could create localized shear-stress during sliding [54], thereby facilitating the cleavage and delamination of the PtSe_2 . This sliding behavior differs from that of widely used solid lubricants such as MoS_2 and graphite. While perfect MoS_2 relies on pristine basal-plane shear and is theoretically moisture-resistant, synthesized polycrystalline films undergo rapid degradation at reactive edge sites and vacancies in humid environments [55]. Furthermore, carbon-based lubricants such as graphite require moisture to passivate reactive edge bonds and enable lubrication [56]. The tribological performance of the PtSe_2 heterostructures, in turn, is not affected by environmental passivation, but rather by localized wear and the residual and transferred particles within the interface.

3.4. Tribological performance of $\text{PtSe}_2/\text{HfO}_2$ heterostructures on 16MnCr5 steel

Taking into account the sliding performance of $\text{PtSe}_2/\text{oxide}$ heterostructures on Si substrates, where HfO_2 demonstrated gradual, simultaneous wear across varying atmospheres whereas Al_2O_3 and TiO_2 OBL exhibited rapid coating wear, tribological testing was conducted on $\text{PtSe}_2/\text{HfO}_2$ heterostructures on 16MnCr5 steel substrate. During the initial sliding stage, the COF of these samples remained at ~ 0.3 in both ambient air and vacuum (Figure 7a). However, in ambient air, a sharp increase in COF was observed within 300 cycles, accompanied by severe wear of both the coating and the counterbody ball (Figures 7b, d, f). In contrast, vacuum testing demonstrated a gradual reduction in COF to 0.2 and an extended tribological durability above 10000 cycles. Under vacuum conditions, no wear was detected on the sliding ball (Figure 7c,g), while the wear track is characterized by a similar wear depth but consisted of numerous high inclusions (Figures 7f,g). This environment-dependent behavior aligns with observations in MXene coatings, where low humidity and vacuum delay mechanical coating breakthrough,

extending tribological lifetime from under 100 cycles in humid air to over 4000 cycles in dry conditions [57]. However, unlike 2D materials such as MXenes or MoSe₂, in which water intercalation weakens interlayer bonding and shifts nanosheets from the central contact zone to the track edges [57-58], the interfacial stability in our PtSe₂/HfO₂ heterostructure binds PtSe₂ inclusions at the wear-track center, ensuring continuous solid lubrication. For comparison, the uncoated 16MnCr5 reference substrate exhibited high friction (COF ~0.8) and severe adhesive wear during vacuum sliding (Figure 7). As reported for steel-on-steel contacts, the absence of environmental moisture in a vacuum prevents the formation of protective, water-assisted surface oxide layers, resulting in un-passivated metallic adhesion and high wear rates [57]. Here, PtSe₂/HfO₂ heterostructures on steel exhibited severe Si₃N₄ ball wear in air (Figure 7b) but no wear in vacuum (Figure 7c). Further, optical topography analyses (Figure 7f, g) confirmed the complete absence of a transfer layer. Unlike carbon materials, MXenes, and MoS₂ that typically rely on friction-induced transfer tribofilms [54], the chemical inertness of PtSe₂ most likely prevents surface bonding and inhibits transfer film formation under vacuum. To gain insight into the underlying wear mechanisms, compositional and chemical analyses of the wear tracks XPS, and EDX elemental mapping (Figures 8–9) were performed.

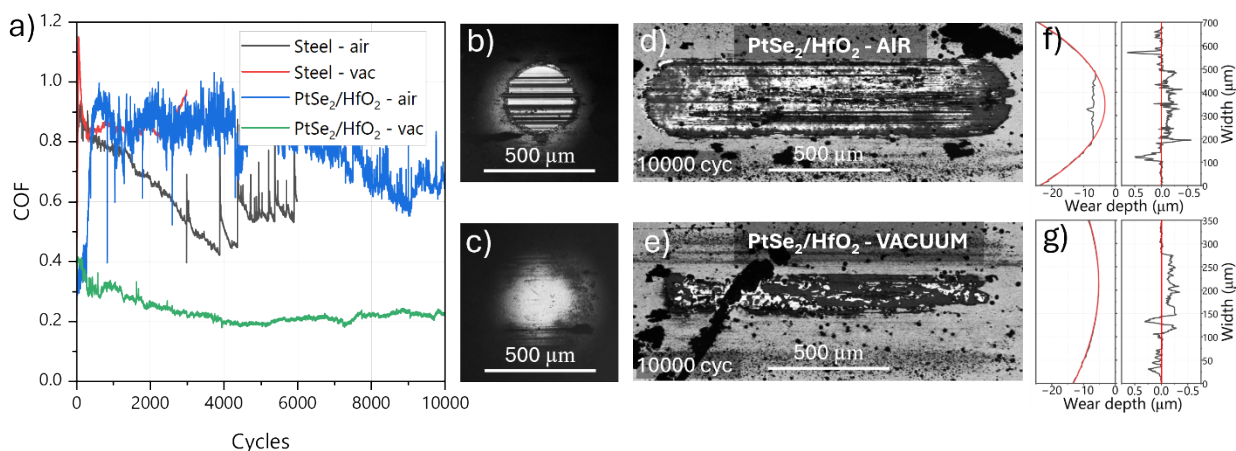


Figure 7. (a) COF versus the number of sliding cycles for PtSe₂ coatings with a HfO₂ OBL on 16MnCr5 steel substrates, evaluated in ambient air and in vacuum. Bare steel references are included for comparison. Optical micrographs of sliding counterbody balls (b, c) and PtSe₂/HfO₂ wear tracks on 16MnCr5 steel substrates (d, e) after 10000 cycles, along with corresponding wear depth profiles (f, g) taken in the middle of the wear track and crated on the ball. (b, d, f) correspond to tests in ambient air, while (c, e, h) correspond to tests in vacuum.

EDX mapping revealed relatively large regions where the Hf signal was significantly reduced for samples tested in ambient air (Figure 8a), whereas a nearly continuous Hf signal was maintained across the wear track for samples tested in vacuum (Figure 8b). These changes indicate that sliding in ambient air causes severe wear on both, PtSe₂ coating and underlying HfO₂ buffer layer. Conversely, the Pt concentration across the wear track in both environments was significantly reduced, existing as localized, weak inclusions. However, the Se distribution exhibited a clear retention pattern, where Pt-containing inclusions inside the wear track overlapped with Se in most cases, suggesting a localized retention of PtSe₂, alongside Se-enriched regions where the Pt signal was absent. Moreover, prominent overlapping of Si and O signals observed mostly in the air-wear track indicates Si₃N₄ counterbody wear and its transfer onto the sample surface.

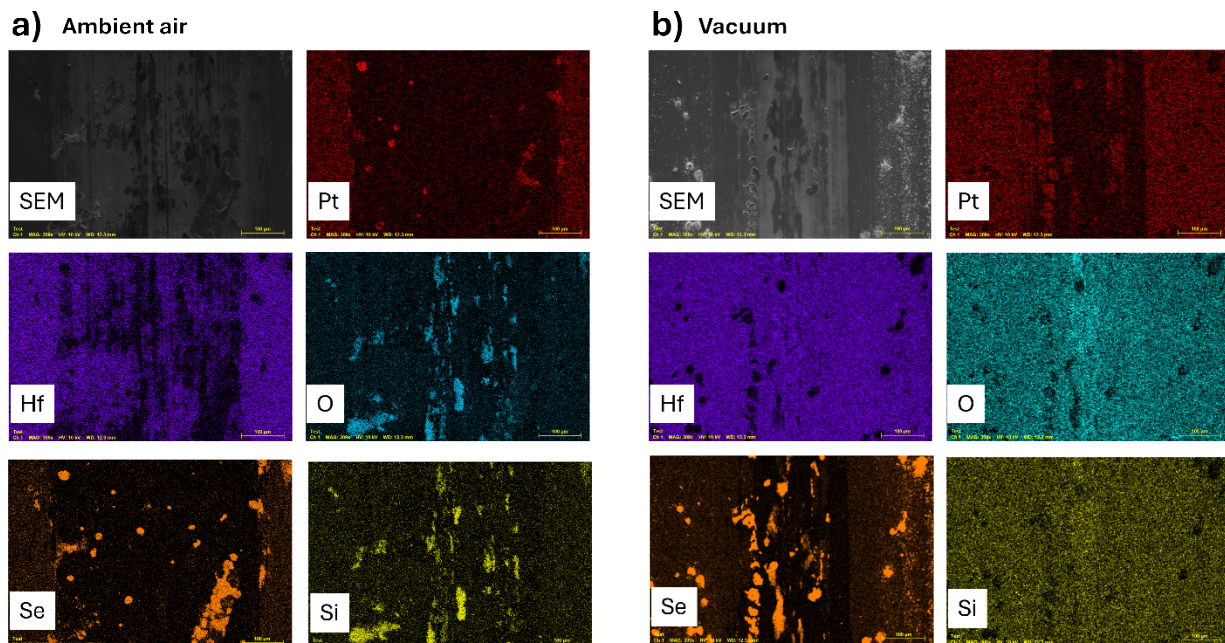


Figure 8. SEM micrographs and EDX elemental maps of the wear tracks formed on PtSe₂/HfO₂/16MnCr5 steel heterostructures tested in ambient air (a) and vacuum (b).

XPS analysis supports the EDX observations and, in addition, demonstrates excellent chemical stability of the heterostructures. High-resolution Pt 4f and Hf 4f core-level spectra (Figure 9) showed no PtSe₂ degradation nor HfO₂ reduction in either testing environment. In particular, the peak shapes and binding energy positions within the wear tracks remained nearly identical to those of the unworn reference area, showing only a reduction in overall intensity due to the decreased amount of material remaining in the contact zone after sliding. In addition to the PtSe₂ characteristic Se 3d_{5/2} and Se 3d_{3/2} doublet peaks, which overlapped with Fe 3p from the steel substrate, the spectra also showed a pronounced signal from elemental Se (Se⁰), and a minor contribution from oxidized Se–O states.

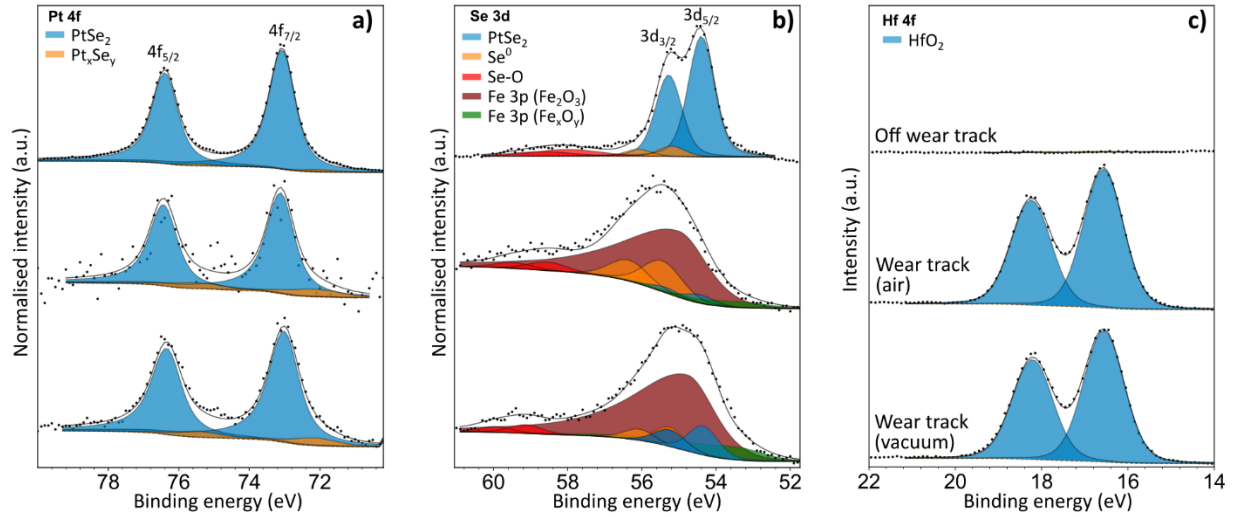


Figure 9. High-resolution (a) Pt 4f, (b) Se 3d, and (c) Hf 4f XPS spectra of the PtSe₂/HfO₂/Steel heterostructure recorded at the unworn sample surface (top), the center of the wear track after testing in ambient air (middle), and the wear track after testing in vacuum (bottom).

These results suggest that relatively high inclusions observed in the wear track depth profiles correspond to retained PtSe₂ inclusions. This retention could be caused by high thermal stability and chemical stability of HfO₂ [59][60], which promotes strong interfacial adhesion with the TMDs film [61]. Combined with low adhesion of PtSe₂ to the sliding counterbody ball, strong interfacial bonding allows the PtSe₂ inclusions to resist removal from sliding contact zone and form easy-shear tribo-film [57]. Anchoring of environmentally stable PtSe₂ inclusions within the wear track suppresses atmospheric effects during early sliding stages. These inclusions can then act as a localized tribofilm that eliminates direct contact between the Si₃N₄ counterbody ball and the steel substrate, thereby reducing friction and wear rate in both ambient air and vacuum. In contrast to MoS₂ coatings, where adsorbed water molecules were proposed to form a protective boundary layer and mitigate oxidation on the inert basal planes of pristine MoS₂ [55][62], PtSe₂ heterostructures studied here are polycrystalline. Therefore, rather than interacting with the inert

PtSe₂ lattice, atmospheric moisture likely adsorbs onto exposed grain boundaries and wear debris [56]. This trapped interfacial water increases capillary drag and facilitates third-body abrasive/adhesive wear in ambient air, resulting in rapid coating failure compared to that under vacuum.

4. Conclusions

The synthesis, structural characteristics, and environmental tribological mechanisms of PtSe₂ films grown on ALD-grown oxide buffer layers (Al₂O₃, HfO₂, and TiO₂) were systematically investigated on Si and 16MnCr5 steel substrates. The choice of interfacial oxide chemistry was shown to play a key role in determining film adhesion, crystallite domain size, and environment-dependent sliding behavior.

On Si substrates, TiO₂ maintained a transfer-film-driven sliding mechanism in both air (COF = 0.18) and vacuum (COF = 0.33) environments. The Al₂O₃ buffer layer exhibited rapid wear in ambient air but achieved a remarkably low COF of 0.08 in vacuum due to localized PtSe₂ inclusions. In contrast, HfO₂ exhibited strong interfacial stability, which supported uniform coating retention across both testing environments.

When applied to 16MnCr5 steel substrates, the PtSe₂/HfO₂ heterostructure demonstrated exceptional solid-lubrication durability under vacuum conditions, exceeding 10000 sliding cycles with a stable COF (~0.2). Structural and compositional characterization revealed that this extended lifetime is driven by strong interfacial bonding between PtSe₂ and HfO₂, combined with low adhesion to the sliding Si₃N₄ counterbody ball. This enables PtSe₂ inclusions to remain strongly anchored within the wear track, providing continuous solid lubrication and preventing substrate damage. In contrast, ambient air exposure accelerates chemical oxidation and film breakdown, limiting wear life to under 300 cycles.

Our findings demonstrate that tailoring interfacial oxide chemistry, specifically utilizing HfO_2 buffer layers, is a highly effective strategy for designing durable PtSe_2 solid-lubricant coatings for vacuum and aerospace applications.

Funding Data

This work was funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V04-00709, and APVV-25-0739.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

2D – Two dimensional

TMD - Transition metal dichalcogenide

OBL - Oxide buffer layer

AFM - Atomic force microscopy

ALD - Atomic layer deposition

TAC - Thermally assisted conversion

COF - Coefficient of friction

EDX / EDS - energy dispersive X-ray spectroscopy

MEMS - Micro-electromechanical systems

RF - Radio frequency

R_{RMS} - Root-mean-square surface roughness (nm)

SEM - Scanning electron microscopy

vdW - van der Waals

XPS - X-ray photoelectron spectroscopy

XRD - X-ray diffraction

References

- [1] Vazirisereshk, M. R., Hasz, K., Zhao, M. Q., Johnson, A. T. C., Carpick, R. W., and Martini, A., 2020, “Nanoscale Friction Behavior of Transition-Metal Dichalcogenides: Role of the Chalcogenide,” *ACS Nano*, **14**(11), pp. 16013–16021.
<https://doi.org/10.1021/acsnano.0c07558>
- [2] Berman, D., Erdemir, A., Zinovev, A. V., and Sumant, A. V., 2015, “Nanoscale Friction Properties of Graphene and Graphene Oxide,” *Diam. Relat. Mater.*, **54**(1), pp. 91–96.
<https://doi.org/10.1016/J.DIAMOND.2014.10.012>.
- [3] Li, Y., Huang, S., Wei, C., Zhou, D., Li, B., Mochalin, V. N., and Wu, C., 2022, “Friction between MXenes and Other Two-Dimensional Materials at the Nanoscale,” *Carbon N. Y.*, **196**, pp. 774–782. <https://doi.org/10.1016/J.CARBON.2022.05.012>.
- [4] Kozak, A., Hofbauerová, M., Halahovets, Y., Pribusová-Slušná, L., Precner, M., Mičušík, M., Orovčík, L., Hulman, M., Stepura, A., Omastová, M., Šiffalovič, P., and Ľapajna, M., 2022, “Nanofriction Properties of Mono- and Double-Layer Ti₃C₂T_xMXenes,” *ACS Appl. Mater. Interfaces*, **14**(32), pp. 36815–36824.
<https://doi.org/10.1021/ACSAMI.2C08963>.
- [5] Wang, Y., Rai, H., and Polcar, T., 2025, “Load-Dependent Sliding Behavior of WSe₂-x Solid Lubricant Coating,” *Wear*, **580–581**, p. 206305.
<https://doi.org/10.1016/J.WEAR.2025.206305>.

- [6] Stoll, J. L., Paul, M., Pritchett, L., Snover, A., Woods, L., Antony Jose, S., and Menezes, P. L., 2025, “Tribology of MXene Materials: Advances, Challenges, and Future Directions,” *Mater. 2025*, Vol. 18, Page 4767, **18**(20), p. 4767.
<https://doi.org/10.3390/MA18204767>.
- [7] Zhou, Q., Maithani, V., Prati, M., Ippolito, S., Creighton, M. A., Gogotsi, Y., Mukherjee, S., and Cao, C., 2025, “Interfacial Shear Strength of MXene Interfaces,” *Cell Reports Phys. Sci.*, **6**(10), p. 102872. <https://doi.org/10.1016/J.XCRP.2025.102872>.
- [8] Kozak, A., Precner, M., Hutár, P., Bodík, M., Vegso, K., Halahovets, Y., Hulman, M., Siffalovic, P., and Ľapajna, M., 2021, “Angular Dependence of Nanofriction of Mono- and Few-Layer MoSe₂,” *Appl. Surf. Sci.*, **567**, p. 150807.
<https://doi.org/10.1016/J.APSUSC.2021.150807>.
- [9] Hye Lee, J., Cho, D.-H., Ho Park, B., -, al, Gnecco, E., Maier, S., Meyer -, E., Yuan, J., Yang, R., and Zhang, G., 2021, “Structural Superlubricity in 2D van Der Waals Heterojunctions,” *Nanotechnology*, **33**(10), p. 102002. <https://doi.org/10.1088/1361-6528/AC1197>.
- [10] Martin, J. M., Pascal, H., Donnet, C., Le Mogne, T., Loubet, J. L., and Epicier, T., 1994, “Superlubricity of MoS₂: Crystal Orientation Mechanisms,” *Surf. Coatings Technol.*, **68–69**(C), pp. 427–432. [https://doi.org/10.1016/0257-8972\(94\)90197-X](https://doi.org/10.1016/0257-8972(94)90197-X).
- [11] Arif, T., Yadav, S., Colas, G., Singh, C. V., and Filleter, T., 2019, “Understanding the Independent and Interdependent Role of Water and Oxidation on the Tribology of Ultrathin Molybdenum Disulfide (MoS₂),” *Adv. Mater. Interfaces*, **6**(22).
<https://doi.org/10.1002/ADMI.201901246>.
- [12] Vierneusel, B., Schneider, T., Tremmel, S., Wartzack, S., and Gradt, T., 2013, “Humidity Resistant MoS₂ Coatings Deposited by Unbalanced Magnetron Sputtering,” *Surf.*

- Coatings Technol., **235**, pp. 97–107. <https://doi.org/10.1016/J.SURFCOAT.2013.07.019>.
- [13] Huang, Y., Gao, H., Yu, K., Niu, Z., Yang, Z., Zhang, B., Gao, K., Zhang, J., and Alpas, A. T., 2025, “Friction Mechanisms of WS₂ in Humid Environments: Investigating H₂O Adsorption via DFT Computations and Sliding Friction Experiments,” *Tribol. Int.*, **203**, p. 110416. <https://doi.org/10.1016/J.TRIBOINT.2024.110416>.
- [14] Cao, H., Wen, F., De Hosson, J. T. M., and Pei, Y. T., 2018, “Instant WS₂ Platelets Reorientation of Self-Adaptive WS₂/a-C Tribocoating,” *Mater. Lett.*, **229**, pp. 64–67. <https://doi.org/10.1016/J.MATLET.2018.06.111>.
- [15] Curry, J. F., Wilson, M. A., Luftman, H. S., Strandwitz, N. C., Argibay, N., Chandross, M., Sidebottom, M. A., and Krick, B. A., 2017, “Impact of Microstructure on MoS₂ Oxidation and Friction,” *ACS Appl. Mater. Interfaces*, **9**(33), pp. 28019–28026. <https://doi.org/10.1021/ACSAMI.7B06917>.
- [16] Li, H., Ju, S., Ji, L., Liu, X., Zhou, H., Chen, J., and Zhao, X., 2023, “Superlubricity of Molybdenum Disulfide Film,” *Surf. Sci. Technol.* 2023 11, **1**(1), pp. 27-. <https://doi.org/10.1007/S44251-023-00027-0>.
- [17] Chen, Y., Li, H., Su, F., Ma, G., Li, Q., Sun, J., and Lin, S., 2023, “Tribological Behavior of MoS₂/a-C:Si Composite Films in High-Temperature Air and Vacuum Environments,” *Tribol. Int.*, **189**, p. 108988. <https://doi.org/10.1016/J.TRIBOINT.2023.108988>.
- [18] Hu, J. J., Bultman, J. E., Muratore, C., Phillips, B. S., Zabinski, J. S., and Voevodin, A. A., 2009, “Tribological Properties of Pulsed Laser Deposited Mo–S–Te Composite Films at Moderate High Temperatures,” *Surf. Coatings Technol.*, **203**(16), pp. 2322–2327. <https://doi.org/10.1016/J.SURFCOAT.2009.02.057>.
- [19] Kubart, T., Polcar, T., Kopecký, L., Novák, R., and Nováková, D., 2005, “Temperature Dependence of Tribological Properties of MoS₂ and MoSe₂ Coatings,” *Surf. Coatings*

- Technol., **193**, pp. 230–233. <https://doi.org/10.1016/j.surfcoat.2004.08.146>
- [20] Ru, G., Qi, W., Sun, S., Tang, K., Du, C., Liu, W., Ru, G., Qi, W., Sun, S., Tang, K., Du, C., and Liu, W., 2024, “Interlayer Friction and Adhesion Effects in Penta-PdSe₂-Based van Der Waals Heterostructures,” *Adv. Sci.*, **11**(34), p. 2400395. <https://doi.org/10.1002/ADVS.202400395>.
- [21] Wang, M., Ru, G., Cui, S., Xu, S., Liu, X., and Qi, W., 2025, “Cooperative Low- and High-Frequency Phonon Dissipation in Penta-PdSe₂: A Key to Structural Superlubricity,” *Surfaces and Interfaces*, **71**, p. 106888. <https://doi.org/10.1016/J.SURFIN.2025.106888>.
- [22] Kim, J. H., Youn, S., Go, T. W., Kim, J., Yoo, C., Shawkat, M. S., Han, S. S., Jeon, S. jae, Jung, Y., Park, J. Y., and Lee, W., 2022, “Revealing Pt-Seed-Induced Structural Effects to Tribological/Electrical/Thermoelectric Modulations in Two-Dimensional PtSe₂ Using Scanning Probe Microscopy,” *Nano Energy*, **91**, p. 106693. <https://doi.org/10.1016/J.NANOEN.2021.106693>.
- [23] Kozak, A., Sojkova, M., Gucmann, F., Bodík, M., Végso, K., Dobrocka, E., Píš, I., Bondino, F., Hulman, M., Šiffalovič, P., and Ľapajna, M., 2022, “Effect of the Crystallographic C-Axis Orientation on the Tribological Properties of the Few-Layer PtSe₂,” *Appl. Surf. Sci.*, **605**, p. 154883. <https://doi.org/10.1016/J.APSUSC.2022.154883>.
- [24] Daws, S., Kotak, P., Kuo, C. N., Shan Lue, C., Politano, A., and Lamuta, C., 2022, “Platinum Diselenide PtSe₂: An Ambient-Stable Material for Flexible Electronics,” *Mater. Sci. Eng. B*, **283**, p. 115824. <https://doi.org/10.1016/J.MSEB.2022.115824>.
- [25] Zhao, Y., Qiao, J., Yu, Z., Yu, P., Xu, K., Lau, S. P., Zhou, W., Liu, Z., Wang, X., Ji, W., and Chai, Y., 2017, “High-Electron-Mobility and Air-Stable 2D Layered PtSe₂ FETs,” *Adv. Mater.*, **29**(5), p. 1604230. <https://doi.org/10.1002/ADMA.201604230>;REQUESTEDJOURNAL:JOURNAL:152140

95;WGROU:STRING:PUBLICATION.

- [26] Tong, Y., Bouaziz, M., Oughaddou, H., Enriquez, H., Chaouchi, K., Nicolas, F., Kubsky, S., Esaulov, V., and Bendounan, A., 2020, “Phase Transition and Thermal Stability of Epitaxial PtSe₂ Nanolayer on Pt(111),” *RSC Adv.*, **10**(51), pp. 30934–30943.
<https://doi.org/10.1039/D0RA04346J>.
- [27] Juo, J. Y., Kern, K., and Jung, S. J., 2024, “Investigation Interface Interactions Between Monolayer and Metals: Implications on Strain and Surface Roughness,” *Langmuir*, **40**(2), pp. 1277–1285. <https://doi.org/10.1021/ACS.LANGMUIR.3C02740>.
- [28] Ke, J., Ying, P., Du, Y., Zou, B., Sun, H., and Zhang, J., 2022, “Delamination of MoS₂/SiO₂ Interfaces under Nanoindentation,” *Phys. Chem. Chem. Phys.*, **24**(26), pp. 15991–16002. <https://doi.org/10.1039/D2CP00074A>.
- [29] Berman, D., Erdemir, A., and Sumant, A. V., 2014, “Graphene: A New Emerging Lubricant,” *Mater. Today*, **17**(1), pp. 31–42.
<https://doi.org/10.1016/J.MATTOD.2013.12.003>.
- [30] Kasbe, P. S., Bosch, J., Bu, J., DellaCorte, C., and Xu, W., 2024, “Scalable Generation of Hybrid Graphene Nanoscrolls for High-Performance Solid Lubricants,” *Tribol. Lett.*, **72**(1), pp. 1–12. <https://doi.org/10.1007/S11249-023-01820-6>.
- [31] Göçerler, H., Danecker, C., Gachot, C., Sui, X., Tomala, A., Rosenkranz, A., Nastran, M., Bayer, B. C., Loni, E., Schwarz, S., Stöger-Pollach, M., and Bilotto, P., 2025, “Unlocking the Synergistic Impact of Laser Texturing and Ti₃C₂T_x MXene Coatings – Substrate-Specific Tribological Insights,” *Carbon N. Y.*, **238**, p. 120270.
<https://doi.org/10.1016/J.CARBON.2025.120270>.
- [32] Sharma, P., Mahadeshwara, M. R., Vilhena, L., Richhariya, V., Silva, F., Ramalho, A., Carvalho, S., and Cavaleiro, A., 2023, “Synergic Effect of TMD Coating on Textured

- Steel Using Micro-EDM,” *Surf. Coatings Technol.*, **467**, p. 129714.
<https://doi.org/10.1016/J.SURFCOAT.2023.129714>.
- [33] Zhang, K., Deng, J., Ding, Z., Guo, X., and Sun, L., 2017, “Improving Dry Machining Performance of TiAlN Hard-Coated Tools through Combined Technology of Femtosecond Laser-Textures and WS₂ Soft-Coatings,” *J. Manuf. Process.*, **30**, pp. 492–501. <https://doi.org/10.1016/J.JMAPRO.2017.10.018>.
- [34] Soldano, C., Ashworth, M. A., Wilcox, G. D., Kutilainen, T., Hokka, J., Praks, J., and Pudas, M., 2021, “Atomic Layer Deposition (ALD) for Environmental Protection and Whisker Mitigation of Electronic Assemblies,” *CEAS Sp. J. 2021 151*, **15**(1), pp. 113–126. <https://doi.org/10.1007/S12567-021-00393-1>.
- [35] Tran, V. H. A., Lims, S. C., Anwar, N., Ahmed, M., Iram, N., Ponnusamy, V. K., and Pham, P. V., 2025, “Atomic Layer Deposition of Metal and Metal Oxides: Mechanisms, Challenges, and Future Prospects,” *J. Alloys Compd.*, **1041**, p. 183864.
<https://doi.org/10.1016/J.JALLCOM.2025.183864>.
- [36] Berini, B., Burcea, R., Vallet, M., Fouchet, A., Aureau, D., Frégnaux, M., Carretero, C., Hurand, S., Demange, V., and Dumont, Y., 2026, “Effect of Various Buffer Layers for the Large-Scale Atomic Layer Deposition Integration of Archetypical SrTiO₃ Thin Film on Silicon Substrate,” *Appl. Surf. Sci.*, **736**, p. 166810.
<https://doi.org/10.1016/J.APSUSC.2026.166810>.
- [37] Li, H. H., Yuan, G. J., Shan, B., Zhang, X. X., Ma, H. P., Tian, Y. Z., Lu, H. L., and Liu, J., 2019, “Atomic Layer Deposition of Buffer Layers for the Growth of Vertically Aligned Carbon Nanotube Arrays,” *Nanoscale Res. Lett. 2019 141*, **14**(1), pp. 119-.
<https://doi.org/10.1186/S11671-019-2947-5>.
- [38] Zhu, Q., Chen, Y., Zhu, X., Sun, Y., Cheng, Z., Xu, J., and Xu, M., 2023, “High-

- Performance near-Infrared PtSe₂/n-Ge Heterojunction Photodetector with Ultrathin Al₂O₃ Passivation Interlayer,” *Sci. China Mater.* 2023 667, **66**(7), pp. 2777–2787.
<https://doi.org/10.1007/S40843-022-2402-3>.
- [39] Sojková, M., Dobročka, E., Hutár, P., Tašková, V., Pribusová Slušná, L., Stoklas, R., Píš, I., Bondino, F., Munnik, F., and Hulman, M., 2021, “High Carrier Mobility Epitaxially Aligned PtSe₂ Films Grown by One-Zone Selenization,” *Appl. Surf. Sci.*, **538**, p. 147936.
<https://doi.org/10.1016/J.APSUSC.2020.147936>.
- [40] Kerherve, G., Skinner, W. S. J., Hochhaus, J. A., Graf, A., Morgan, D. J., Isaacs, M. A., Reed, B. P., Nakajima, H., and Payne, D. J., 2026, “KherveFitting: An Open Source Software for Fitting X-Ray Photoelectron Spectroscopy Data,” *Surf. Interface Anal.*, **58**(1), pp. 54–65. <https://doi.org/10.1002/SIA.70032>.
- [41] Belo, G. S., Nakagomi, F., Minko, A., Da Silva, S. W., Moraes, P. C., and Buchanan, D. A., 2012, “Phase Transition in Sputtered HfO₂ Thin Films: A Qualitative Raman Study,” *Appl. Surf. Sci.*, **261**, pp. 727–729. <https://doi.org/10.1016/J.APSUSC.2012.08.088>.
- [42] Li, S., Zhang, Y., Yang, D., Yang, W., Chen, X., Zhao, H., Hou, J., and Yang, P., 2020, “Structure and Optical Properties of HfO₂ Films on Si (100) Substrates Prepared by ALD at Different Temperatures,” *Phys. B Condens. Matter*, **584**, p. 412065.
<https://doi.org/10.1016/J.PHYSB.2020.412065>.
- [43] Lee, S., Yoon, H., Lee, S., Chung, S. min, and Kim, H., 2024, “Investigation of the Hydrophilic Nature and Surface Energy Changes of HfO₂ Thin Films Prepared by Atomic Layer Deposition,” *Vacuum*, **219**, p. 112756.
<https://doi.org/10.1016/J.VACUUM.2023.112756>.
- [44] Zeng, X., Peng, Y., and Lang, H., 2017, “A Novel Approach to Decrease Friction of Graphene,” *Carbon N. Y.*, **118**, pp. 233–240. [10.1016/j.carbon.2017.03.042](https://doi.org/10.1016/j.carbon.2017.03.042)

- [45] Wang, Y., Li, L., Yao, W., Song, S., Sun, J. T., Pan, J., Ren, X., Li, C., Okunishi, E., Wang, Y. Q., Wang, E., Shao, Y., Zhang, Y. Y., Yang, H. T., Schwier, E. F., Iwasawa, H., Shimada, K., Taniguchi, M., Cheng, Z., Zhou, S., Du, S., Pennycook, S. J., Pantelides, S. T., and Gao, H. J., 2015, “Monolayer PtSe₂, a New Semiconducting Transition-Metal-Dichalcogenide, Epitaxially Grown by Direct Selenization of Pt,” *Nano Lett.*, **15**(6), pp. 4013–4018. <https://doi.org/10.1021/ACS.NANOLETT.5B00964>.
- [46] Alexander V. Naumkin, Anna Kraut-Vass, Stephen W. Gaarenstroom, and C. J. P., 2012, “NIST X-Ray Photoelectron Spectroscopy Database,” *Meas. Serv. Div. Natl. Inst. Stand. Technol.*, **20899**(20), p. 20899. <https://doi.org/10.18434/T4T88K>.
- [47] Hrdá, J., Vegso, K., Shaji, A., Nádaždy, P., Krajčovičová, T. E., Pribusová Slušná, L., Bernstorff, S., Jergel, M., Siffalovic, P., Hulman, M., and Sojková, M., 2026, “In Situ X-Ray Scattering Investigation of PtSe₂ Grown via Thermally Assisted Conversion,” *Nano Express*, **7**(2), p. 025015. <https://doi.org/10.1088/2632-959X/AE72AA>.
- [48] He, X., Zhang, Y., Yang, X., Zhang, Z., and Wang, R., 2026, “Regulation Strategies for CVD Growth of Non-Layered 2D Materials,” *Nano Res.*, **19**(1), p. 94908214. <https://doi.org/10.26599/NR.2025.94908214>.
- [49] Bregliozzi, G., Di Schino, A., Kenny, J. M., and Haefke, H., 2003, “The Influence of Atmospheric Humidity and Grain Size on the Friction and Wear of AISI 304 Austenitic Stainless Steel,” *Mater. Lett.*, **57**(29), pp. 4505–4508. [https://doi.org/10.1016/S0167-577X\(03\)00351-3](https://doi.org/10.1016/S0167-577X(03)00351-3).
- [50] Polcar, T., Evaristo, M., Stueber, M., and Cavaleiro, A., 2009, “Mechanical and Tribological Properties of Sputtered Mo–Se–C Coatings,” *Wear*, **266**(3–4), pp. 393–397. <https://doi.org/10.1016/J.WEAR.2008.04.010>.
- [51] Blau, P. J., 2005, “On the Nature of Running-In,” *Tribol. Int.*, **38**(11–12), pp. 1007–1012.

- <https://doi.org/10.1016/J.TRIBOINT.2005.07.020>.
- [52] Benincá, F. P., Romero, M. C., Camporez, R. M., Neto, C. A. R., Strey, N. F., and Scandian, C., 2023, “Evolution of Morphology, Microstructure and Hardness of Bodies and Debris during Sliding Wear of Carbon Steels in a Closed Tribosystem,” *Wear*, **523**, p. 204809. <https://doi.org/10.1016/J.WEAR.2023.204809>.
- [53] He, D., Shang, L., Li, W., Cheng, B., Zhai, H., Zhang, X., Lu, Z., and Zhang, G., 2023, “Friction-Induced Reconstruction of Sliding Interface and Low Friction Mechanism of WC/a-C Films,” *Mater. Des.*, **226**, p. 111640. <https://doi.org/10.1016/J.MATDES.2023.111640>.
- [54] Liu, Y., Chen, L., Zhang, B., Cao, Z., Shi, P., Peng, Y., Zhou, N., Zhang, J., and Qian, L., 2019, “Key Role of Transfer Layer in Load Dependence of Friction on Hydrogenated Diamond-Like Carbon Films in Humid Air and Vacuum,” *Mater.* 2019, Vol. 12, Page 1550, **12**(9), p. 1550. <https://doi.org/10.3390/MA12091550>.
- [55] Zhao, X., Zhang, G., Wang, L., and Xue, Q., 2017, “The Tribological Mechanism of MoS₂ Film under Different Humidity,” *Tribol. Lett.* 2017 652, **65**(2), pp. 64-. <https://doi.org/10.1007/S11249-017-0847-3>.
- [56] Song, H., Ji, L., Li, H., Wang, J., Liu, X., Zhou, H., and Chen, J., 2017, “Self-Forming Oriented Layer Slip and Macroscale Super-Low Friction of Graphene,” *Appl. Phys. Lett.*, **110**(7). <https://doi.org/10.1063/1.4975979>.
- [57] Marian, M., Song, G. C., Wang, B., Fuenzalida, V. M., Krauß, S., Merle, B., Tremmel, S., Wartzack, S., Yu, J., and Rosenkranz, A., 2020, “Effective Usage of 2D MXene Nanosheets as Solid Lubricant – Influence of Contact Pressure and Relative Humidity,” *Appl. Surf. Sci.*, **531**, p. 147311. <https://doi.org/10.1016/J.APSUSC.2020.147311>.
- [58] Alshammari, S., Harvey, T., and Wang, S., 2025, “Comparative Study of the Tribological

- Properties of MoSe₂ Coatings Under Dry and Oil-Lubricated Sliding Conditions,” *Lubr.* 2025, Vol. 13, Page 467, **13**(11), p. 467. <https://doi.org/10.3390/LUBRICANTS13110467>.
- [59] Qiu, X., Howe, J. Y., Meyer, H. M., Tuncer, E., and Paranthaman, M. P., 2011, “Thermal Stability of HfO₂ Nanotube Arrays,” *Appl. Surf. Sci.*, **257**(9), pp. 4075–4081. <https://doi.org/10.1016/J.APSUSC.2010.11.178>.
- [60] Yu, H. Y., Wu, N., Li, M. F., Zhu, C., Cho, B. J., Kwong, D. L., Tung, C. H., Pan, J. S., Chai, J. W., Wang, W. D., Chi, D. Z., Ang, C. H., Zheng, J. Z., and Ramanathan, S., 2002, “Thermal Stability of (HfO₂)_x(Al₂O₃)_{1-x} on Si,” *Appl. Phys. Lett.*, **81**(19), pp. 3618–3620. <https://doi.org/10.1063/1.1519733>.
- [61] Azcatl, A., Kc, S., Peng, X., Lu, N., McDonnell, S. S., Qin, X., De Dios, F., Rafik, A., Kim, J., Kim, M. J., Cho, K., and Wallace, R. M., 2015, “HfO₂ on UV–O₃ Exposed Transition Metal Dichalcogenides: Interfacial Reactions Study,” *2D Mater.*, **2**(1), p. 014004. <https://doi.org/10.1088/2053-1583/2/1/014004>.
- [62] Khare, H. S., and Burris, D. L., 2013, “The Effects of Environmental Water and Oxygen on the Temperature-Dependent Friction of Sputtered Molybdenum Disulfide,” *Tribol. Lett.* 2013 523, **52**(3), pp. 485–493. <https://doi.org/10.1007/S11249-013-0233-8>.