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Smart Vehicle Glazing Using W-Doped VO_2 and TiO_2 for Sunlight-Responsive Tinting

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Abstract

This study explores an abrupt coating for vehicle windshields that can adjust its tint or shade in response to sunlight and temperature. The proposed design is a multilayer film in which a tungsten(W)-doped vanadium dioxide (VO_2) layer is placed between two titanium dioxide (TiO_2) layers. With the natural ability of VO_2 of changes from clear to reflective as its surface warms, and the addition of tungsten allows this shift to occur at a lower temperature, roughly 35-40 °C, which is more appropriate for the climate in Saudi Arabia. The TiO_2 layers help rally the overall clarity of the film and support photo-activation when exposed to UV and near-infrared light, allowing the coating to react more to sunlight than to ambient heat. As a result, the tint develops gradually during strong daylight yet remains clear at night. Simulation work carried out in this study indicates that the coating can reduce glare and solar heat without the need for sensors or electrical power. While still conceptual, the approach shows promise for enhancing driving comfort and visibility in hot regions and may support the development of simple, energy-free tinting solutions for vehicles.

Keywords
Photo-Thermochromic Coating, W-Doped VO_2 Smart Film, Passive Tint Regulation, Multilayer Nanostructure Glazing, Solar-Responsive Automotive Windshield

1. Introduction
Despite continuous progress in automotive technology and safety systems, sun glare is still a major issue that affects drivers around the world. Even with improvements in vehicle comfort, reliability, and overall design, bright sunlight and the heat it generates inside the cabin remain serious concerns, particularly in hot regions such as Saudi Arabia. Glare from direct sunlight can reduce a driver's capability to see clearly and may contribute to accidents. Common solutions like sun visors or fixed tinted glass often fall short because they block only part of the windshield or reduce

visibility in other situations. More advanced options, such as electrochromic or PDLC-based systems, can adjust their tint but depend on electrical power and added control components, which increases their cost and complexity. In response to these challenges, earlier work (Cui et al., 2018) introduced a passive smart-tinting concept that relies on thermochromic materials capable of adjusting to sunlight and temperature on their own, without sensors or external power.

Vanadium dioxide (VO_2) is well known for its ability to change from an insulating state to a metallic one when heated to around 68 °C, a shift that greatly reduces infrared transmission while still allowing visible light to pass. For vehicle applications, however, this temperature is higher than ideal. Researchers have found that adding small amounts of tungsten (W) can lower the transition point considerably. As noted in (X. Chen et al., 2019), even a modest level of W doping can bring the switching temperature down to roughly from 35 to 45 °C, which aligns much better with the conditions typically seen on sun-exposed automotive glass. With this adjustment, the material can begin to dim under moderate heat, helping cut down glare and reduce cabin temperatures while remaining clear during nighttime. Although VO_2 coatings have been used in building windows, which usually rely on undoped VO_2 and are designed primarily for energy efficiency rather than improving driver visibility and comfort.

To strengthen the coating's response to sunlight, this work uses a multilayer design that combines TiO_2 with VO_2. The TiO_2 layers play an important role: they help maintain good optical clarity and support photo-assisted activation. When exposed to direct sunlight, TiO_2 absorbs UV and near-infrared radiation, creating localized warming that encourages the VO_2 layer to switch at a lower effective temperature. According to (Zhao et al., 2022a), this type of photo-thermochromic configuration makes the tinting behavior depend more on sunlight intensity than on the surrounding air temperature. With this mechanism in place, the coating stays clear during warm evenings but gradually darkens under bright daytime conditions. The resulting $TiO_2/W - VO_2/TiO_2$ structure offers a passive and gradual tint change that supports safer visibility for drivers. Since improving road safety and encouraging technological innovation are priorities under Saudi Vision 2030, this concept aligns well with ongoing national efforts to promote practical, home-grown engineering solutions.

1.1 Objectives

The major goals of this work include:

- To develop a sensor-free, temperature- and sunlight-responsive smart tinting film using W-doped VO_2 within a $TiO_2 - ViO_2 - TiO_2$ multilayer for automotive windscreen applications.
- To ensure safe and selective tinting through a hybrid photo-thermochromic system that activates solar exposure but remains transparent during nighttime or low-light conditions.
- To demonstrate the feasibility of a multilayer VO_2/TiO_2 structure that enhances driver comfort, reduces glare, and supports sustainable, energy-independent automotive design aligned with local climate conditions.
- Supporting the goals of Saudi Vision 2030 by promoting innovation, safety, and sustainable engineering solutions that improve the quality of life.

2. Literature Review

Glare Reduction and Road Safety

Excessive sun glare is a well-documented driving hazard, capable of temporarily blinding drivers and increasing the risk of accidents (Guo et al., 2023). Conventional countermeasures like sun visors and sunglasses only partially mitigate this problem, they often leave portions of the windshield unprotected and require constant manual adjustment, which can distract the driver. Recent studies highlight the need for adaptive glare reduction systems integrated into the windshield. For example, R. I. Nugroho, S. Suhendra and M. R. D. Aditama, 2025 developed a smart film using Polymer-Dispersed Liquid Crystal (PDLC) that automatically dims in response to intense light, blocking up to 99% of incoming glare while remaining transparent under normal conditions. This dynamic glare-control approach can significantly reduce visual strain and improve forward visibility during bright sunlight yet return to a high-transparency state in low-light or nighttime conditions. The challenge moving forward is to ensure any such adaptive tint maintains sufficient clarity (legal windshield transparency is typically ≥70% visible light transmission, also known as "VLT") when glare is absent (Guo et al., 2023). These findings underscore that a passive smart windscreen film, one that darkens automatically under bright sun and clears otherwise, could markedly enhance driving safety if it balances glare reduction with all-hours visibility.

Thermochromic Behavior and Fundamentals of VO_2

Vanadium dioxide (VO_2) is widely recognized for its thermochromic properties, with a reversible phase transition from an insulating to metallic state around 68 °C. Above this temperature, VO_2 reflects infrared radiation, making it useful for heat regulation. However, this temperature is too high for practical applications like automotive glazing. To address this, researchers have explored doping methods, particularly tungsten (W) doping. Studies of Jiang et al., 2024 and Majid et al., 2020 show that even 1-2% W can reduce the transition temperature to around 30-40 °C, aligning better with environmental conditions inside vehicles. Tungsten introduces additional electrons into the VO_2 lattice, destabilizing the insulating phase and enabling earlier switching. Furthermore, Bleu et al., 2023a confirmed that W-doping narrows the thermal hysteresis and improves the optical properties of the film. These modifications are essential for developing VO_2-based coatings tailored to real-world temperature ranges encountered in vehicles.

Photo-Assisted Hybrid Materials for Daytime-Selective Activation
To improve the selectivity of smart tinting and avoid nighttime activation, researchers have integrated VO_2 with photoresponsive materials. Titanium dioxide (TiO_2), a UV-active semiconductor, can enhance solar absorption and trigger earlier transitions in VO_2 films. Ji et al., 2019a showed that TiO_2/VO_2 bilayers offer improved luminous transmittance and self-cleaning performance. Another work of Xie et al., 2021, explores core-shell structures using ZnO or SiO_2 as outer layers can further enhance durability and provide UV protection. More recently, Zhao et al., 2022b reviewed how photothermal additives-such as carbon nanoparticles, TiN, and Cs_xWO_3 can assist solar-induced heating and lower the effective switching temperature of VO_2 films under sunlight. These hybrid approaches ensure the tinting occurs mainly under solar irradiation and remains clear in the absence of daylight, making them especially suitable for passive automotive applications.

Smart Windows in Buildings vs. Automotive Challenges
VO_2 smart coatings have been tested extensively in buildings for passive energy savings. However, the standards for visible light transmission (VLT) are more relaxed in buildings than in vehicles. In automotive glazing, safety regulations typically require $VLT \geq 70\%$, making optical clarity a key limitation for VO_2 films. To adapt VO_2 for automotive use, transparency must be improved. Ji et al., 2019b and Y. Chen et al., 2017 achieved higher visible transmittance and weather stability using TiO_2 or ZnO layers. Vehicle applications also demand greater mechanical durability and consistent performance across varying conditions, from high sunlight to nighttime driving. Protective layering and careful doping have shown promise, but full automotive adoption remains limited due to these strict requirements.

Although thermochromic materials like VO_2 have been widely studied for use in smart glazing, especially in architectural applications, their adaptation to automotive windscreen systems remains limited. Most existing efforts prioritize static building windows where moderate tinting and slower response times are acceptable. However, little attention has been given to developing a passive, sensor-free, and optically clear thin-film solution tailored to vehicle-specific conditions. This study addresses that gap by introducing a dual-doped, photo-thermochromic VO_2-based system enhanced with TiO_2, engineered to provide selective daytime tinting while maintaining clear night-time visibility. The project aims to demonstrate a technically feasible and practical solution for glare reduction and thermal comfort in vehicles without relying on external power sources or complex control systems.

3. Methods

3.1 Idea Development

The idea for the Vanadium Sun Tint project was developed while studying the "Engineering Design" course, where a systematic design approach guided us to identify real-world problems. The process began with understanding engineering needs and gradually evolved through creativity, evaluation, and ethical considerations. Figure 1 illustrates the key stages through which the student's learning and project idea progressed during the course.

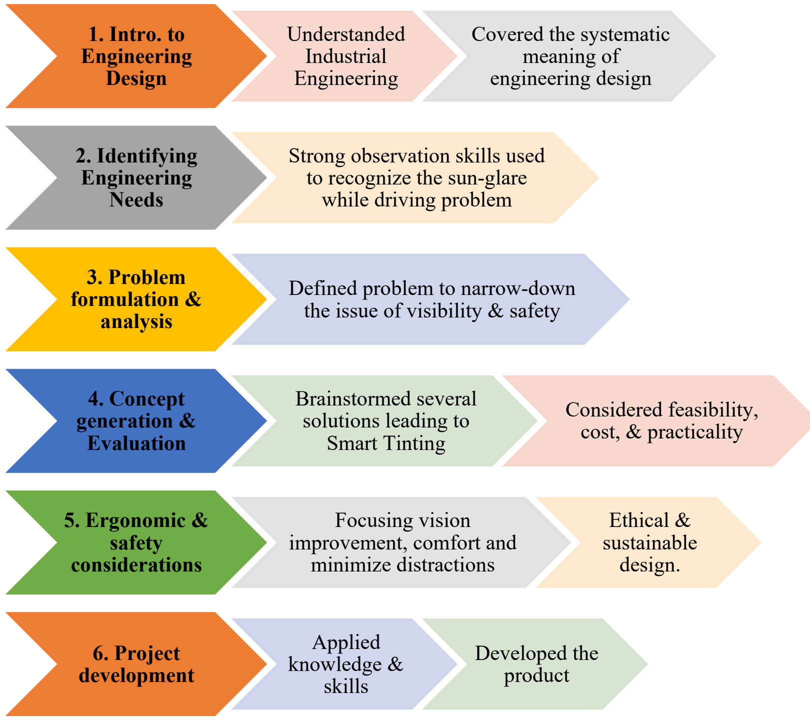

Figure 1. Process Flow of Idea Development through the Engineering Design Course

The well-recognized heat in Saudi Arabia makes vehicle interiors uncomfortably hot. When the sun visor on our car broke one day, the need for a better shading solution became apparent. Vehicle cabin temperatures can rise substantially above ambient: measured studies in hot-sun conditions show cabin air temperatures exceeding 50 °C (for example, 53.9 °C with an ambient of 34.1 °C), and under extreme, stagnant conditions, peak cabin temperatures in the literature have approached or exceeded 60 °C. These elevated cabin temperatures (often 20–30 °C higher than ambient) are associated with reduced driver comfort and increased safety risk, which supports the need for an effective, easily deployable shading solution. The average temperature variance (Al-Rawashdeh et al., 2021), (Grundstein et al., 2009) is presented in Figure 2.

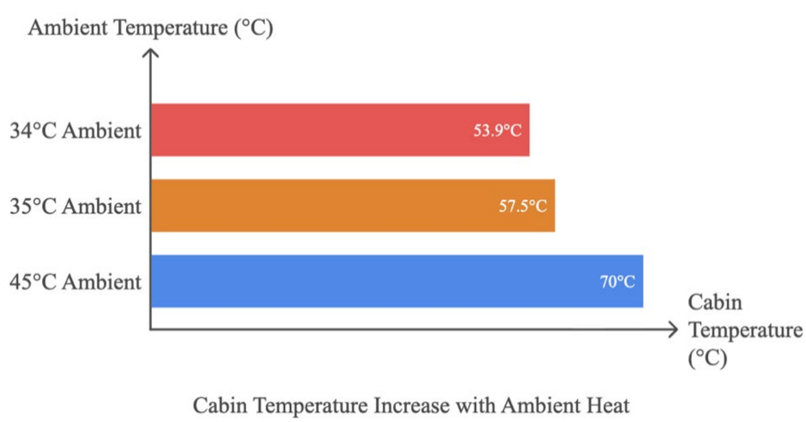

Figure 2. Average temperature in Saudi Arabia

3.2 Problem Statement

Excessive sunlight entering through the front windshield of vehicles not only raises the cabin temperature but can also expose drivers to very high luminance levels, far beyond those under which the human eye achieves optimal acuity (~3,000–5,000 cd/m²). Studies of glare show that bright light within the field of view reduces contrast and impairs visibility, increasing driver fatigue and disruption. Table 1 offers estimated luminance values for typical daylight and direct sunlight conditions, intended as illustrative rather than definitive (Hunt & Pointer, 2011). This intensity, combined with trapped heat, reduces driver concentration, increases fatigue, and in some cases, makes vehicles undrivable during peak sunlight hours (Table 1).

Table 1. Average brightness with the weather

Environment	Approx. Brightness	Driving Comfort Level
Cloudy Day	1,000–2,000 (cd/m²)	Comfortable
Clear Day (Mid-day)	10,000–20,000 (cd/m²)	Uncomfortable
Direct Sun on Windshield	25,000+ (cd/m²)	Unsafe glare

From this need, the idea for a smart, heat-responsive front-window tint emerged, a product that could automatically darken when exposed to intense sunlight and help maintain significantly lower interior temperatures. Studies on solar-reflective and thermochromic glazing technologies have demonstrated that such systems can lower vehicle surface and cabin temperatures by up to 15°C under optimal conditions (Wu et al., 2018), depending on sunlight intensity and material configuration. By targeting this level of performance, the product aims to bring interior conditions back into a more acceptable and drivable range, especially during the extreme heat typical of Saudi summers.

3.3 Vanadium Dioxide (VO_2) Proposal

During concept development, vanadium dioxide (VO_2) has been selected as the active thermochromic material because it changes optical behavior around 40°C, which closely matches the threshold many drivers consider unsafe. When the surface temperature of the glass reaches this point, the VO_2 layer automatically transitions from a transparent to a reflective state, effectively reducing both infrared heat and visible light intensity within the car cabin. Notably, this occurs without requiring electrical power or manual adjustment.

To ensure the windscreen's tint practicality, multiple configurations are evaluated based on clear design criteria: maintain high visible clarity at night, provide strong heat rejection in direct sunlight, remain removable and reusable, resist everyday wear, and maintain a low cost to ensure accessibility for the average driver. The chosen concept consists of a thin, flexible film coated with stacked VO_2-based layers, which allow for gradual darkening rather than a single abrupt change at 40°C (Manning et al., 2002a).

3.4 Gradual Darkening Behavior of Stacked VO_2

The tint is designed so that any visible darkening remains within Saudi vehicle regulation limits, ensuring it is not considered illegal. During summer months in Saudi Arabia, nighttime temperatures in many inland urban areas often fall into the mid-20s °C range (e.g., ~25-30 °C), and though they may approach 33 °C in some extreme cases, they rarely exceed 35 °C (Seman & Wolden, 2004). The relationship between visible light transmission and temperature (Manning et al., 2002b) is shown in Figure 3. This curve is derived from our optical simulation of the multilayer structure and illustrates the gradual decrease in transmission near the transition point.

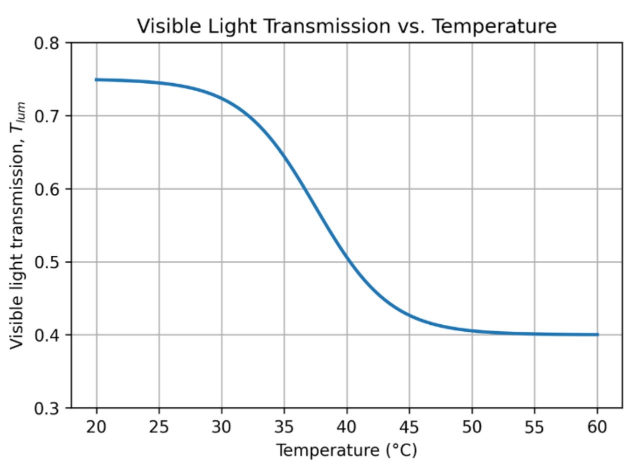

Figure 3. Simulated visible light transmission vs. temperature

As a result, the tint remains transparent and fully compliant for night driving. Prototype planning focused on practicality and usability. This included pre-cut sizes for common vehicle models, a mounting method that prevents slipping without leaving residue, foldable storage, and a user guide for quick installation and removal. Performance targets were set to ensure that the film activates at approximately 40°C, reduces cabin heat by 15-20°C, and maintains sufficient light transmission for safe driving visibility, measured in candela per square meter levels consistent with daytime standards.

3.5 W-doped Vanadium Dioxide (VO_2)

Pure vanadium dioxide (VO_2) is a thermochromic material that changes from an insulating to a metallic phase near 68 °C, reflecting near-infrared (NIR) radiation while allowing visible light to pass. However, this high transition temperature makes pure VO_2 unsuitable for vehicle windscreens, as tinting would only occur at extreme heat levels. To address this, tungsten (W) doping is used to lower the transition temperature (T_p) by increasing the electron concentration in the VO_2 lattice. With approximately 1-2% W (Bleu et al., 2023b), the transition temperature decreases from about 68 °C to 32-40 °C, aligning with realistic automotive glass surface temperatures. This adjustment enables VO_2 to provide automatic, temperature-responsive tinting in response to normal sunlight, offering passive glare and heat control without external power or sensors.

3.6 Photo-thermochromic Hybrid System

Although W-doping lowers the activation temperature, the tinting still depends only on heat. This may cause unwanted darkening during hot nights without sunlight. To overcome this, a photo-thermochromic hybrid system is developed by combining W-doped VO_2 with titanium dioxide (TiO_2) layers. Tungsten lowers the thermal switching point, while titanium dioxide (TiO_2) enables photo-assisted activation via ultraviolet (UV) and near-infrared (NIR) absorption. TiO_2 enhances local heating under sunlight, making the transition primarily responsive to solar radiation instead of ambient warmth. The designed multilayer structure (TiO_2 / $W - VO_2$ / TiO_2) improves luminous transmittance (>70%), prevents oxidation, and ensures tinting occurs only under sunlight. This multilayer, photo-thermochromic system with W-doped VO_2 thus provides a controlled, sunlight-dependent tint-clear at night and dynamically responsive during the day, ensuring both driver safety and energy efficiency. The relevant thickness of each layer of materials with their function is given in Table 2.

Table 2. Tint material layers

Layer	**Material**	**Thickness**	**Function**
Top	TiO_2	40-60 nm	UV absorption, photo-activation of VO_2, anti-reflection
Middle	VO_2	50-100 nm	Thermochromic layer (main tinting agent)
Bottom	TiO_2	20-40 nm	Optical matching to substrate, barrier for diffusion
Windscreen	Glass or polymer substrate	3.5 mm	Protect the vehicle interior while driving from wind and dust.

3.7 Optical Simulation

To evaluate the optical performance of the proposed smart coating, spectral transmittance and reflectance simulations were conducted using the transfer matrix method (TMM). This technique models light propagation through multi-layer thin films by multiplying characteristic matrices for each layer to obtain the overall system response. The stack consisted of a 50 nm TiO_2 antireflection layer, an 80 nm W-doped VO_2 layer, and a 30 nm TiO_2 bottom layer on a thick glass substrate (Table 2). Complex refractive indices were taken from literature: TiO_2 has a refractive index of approximately 2.65 with negligible absorption across the visible and near-infrared range (Salazar et al., 2015), VO_2 exhibits n≈2.79 and low extinction in the insulating state and n≈2.44 with higher absorption when metallic (Wan et al., 2019). Air and glass were modelled as n = 1.0 and n = 1.5, respectively.

Functional response under Thermal and Optical Stimuli

The proposed $W - VO_2/TiO_2$ The system responds simultaneously to temperature and sunlight, producing a gradual tint rather than a sudden change. Below 30 °C, both layers stay transparent, maintaining full visibility. As the glass warms under sunlight to around 35 °C, the W-doped VO_2 begins its phase transition while reflecting near-infrared (NIR) radiation, maintaining high visible-light clarity. This creates a mild tint that reduces glare and solar heat. At about 45 °C, the TiO_2 layer becomes photoactive under UV and NIR light, generating localized heat that enhances the VO_2 transition. Tint intensity increases smoothly with sunlight strength and reverses when the light or temperature drops (Mongstad et al., 2014). This stepwise behavior allows the windshield to darken automatically in strong sunlight and remain clear at night, ensuring safe, sensor-free, and energy-independent tint control suitable for vehicles.

4. Results and Discussion

4.1. Simulated Structural Interpretation:

Due to limitations in accessing experimental lab tools, the morphology of the proposed smart coating was studied through atomistic simulation and digital modeling. Using BIOVIA Materials Studio, a multi-layer system of TiO_2/W-VO_2/TiO_2 was designed, revealing its crystalline texture, and visualized at the nanoscale to understand its expected surface behavior and layer uniformity. The structure was configured with realistic doping concentration and spacing based on known crystallographic parameters.

These simulations enabled the observation of morphological features such as grain boundary textures, surface uniformity, and the arrangement of material interfaces. Such insights help predict optical and thermochromic behavior, as the microstructure directly influences light scattering, thermal conductivity, and tinting response. While not a substitute for physical imaging, the modeling approach provided a controlled environment to evaluate the coating's performance and guide future experimental fabrication.
This structure is crucial for achieving the reversible optical change near 40°C, the threshold at which the tint begins to darken (Table 3).

Numerical Results
The TiO_2/W-VO_2/TiO_2, a multilayer coating was evaluated using transfer-matrix optical simulations. Because no experimental measurements were possible in this study, the following values represent predicted or target specifications derived from our modelling and from reported data in the literature. They provide guidance for future fabrication efforts but should not be interpreted as measured performance. The simulated multilayer offers:

- Highly visible transmittance T_{lum}≈ 60-70%
- Strong solar modulation ΔT_{sol} = up to 15-20%
- Reduced reflection and improved durability
- Resistance to oxidation and humidity

Table 3. Target tinting of material

Metric	**Predicted/target value**	**Source/method**
Visible transmittance (T_{lum})	60-70%	Predicted by a multilayer optical simulation
Solar modulation (ΔT_{sol})	15-20%	Predicted by simulation and consistent with the reported performance of W-doped VO_2 coatings (Song et al., 2023)

4.2 Graphical Results

To test our prospective multilayered coating, we have used two different approaches. First, to observe the microstructural morphologies of material, the BIOVIA Materials Studio 2024 (24.1.0) is used, then to observe the optical simulation, the TMM technique is written in Python 3.11 on a 64-bit Windows 11 OS 11th Intel Core i5-11400H at 2.70 GHz with 6 physical cores and 12 logical processors, along with 8GB RAM. Figure 4 and Figure 5 display the 3D and top-view morphology of TiO_2. The surface appears relatively smooth with minor grain texture, indicating good film uniformity. This morphology is beneficial for optical clarity, light transmission, and photocatalytic stability, which are key for the outer protective layers in the multilayer system.

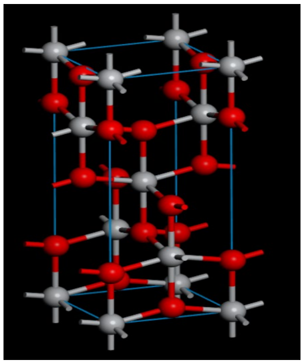

Figure 4. 3D morphology of TiO_2

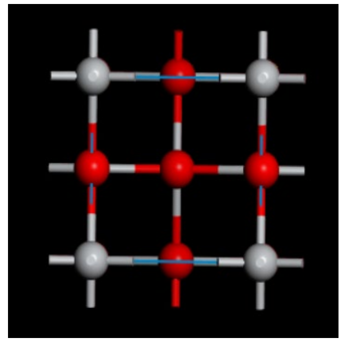

Figure 5. Top view of TiO_2 morphology

Figures 6 and 7 represent the 3D and top-view of the W-doped VO_2 layer. The structure shows more prominent granularity, reflecting its crystalline nature and thermochromic behavior. These irregularities suggest high surface activity, supporting efficient near-infrared (NIR) modulation and thermal response at the target transition temperature.

Figures 8 and 9 illustrate the combined morphology of the multilayer $TiO_2/W - VO_2/TiO_2$ coating. The layering appears distinct, with the VO_2 core embedded between relatively flatter TiO_2 outer surfaces. The integration maintains structural continuity while allowing functional variation across the thickness. This layered arrangement is critical for achieving both visible light transparency and temperature-activated solar reflection, enabling smooth, reversible tinting tailored for vehicle windshields.

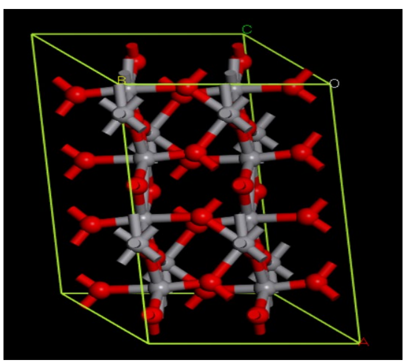

Figure 6. 3D morphology of $W - VO_2$

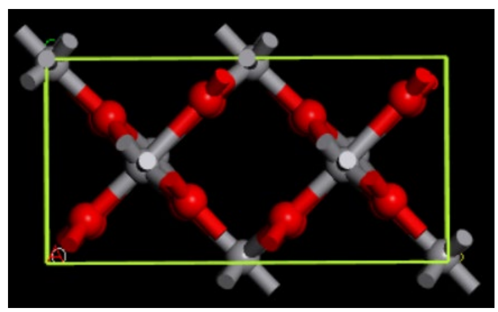

Figure 7. Top-view of $W - VO_2$ morphology

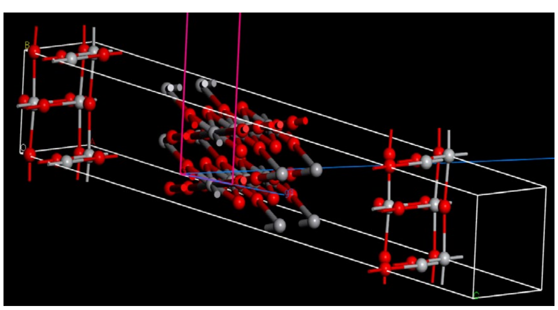

Figure 8. 3D morphology of $TiO_2/W - VO_2/TiO_2$

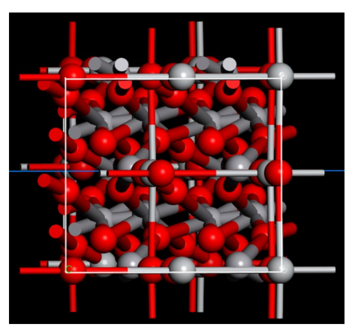

Figure 9. Top view of $TiO_2/W - VO_2/TiO_2$ morphology

Simulations were implemented in Python using an open-source TMM program. The simulated transmittance and reflectance curves display interference fringes characteristic of thin-film multilayers. In the cold, insulating state, constructive interference yields high visible transmittance (~54 %), whereas in the hot, metallic state, absorption in the VO_2 layer reduces transmittance and increases reflectance. The peaks correspond to wavelengths where the optical path lengths satisfy constructive interference conditions.

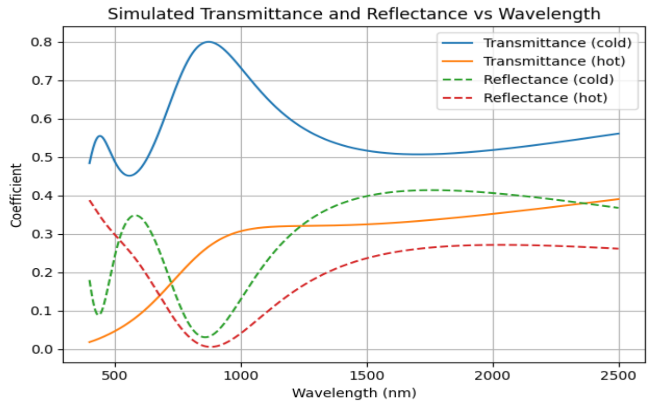

Figure 10. Simulated transmittance spectra

Averaging over the solar spectrum, the calculated visible transmittance of the stack is ~54 % in the cold state and ~9 % in the hot state; average solar transmittance drops from ~57 % to ~29 %, giving a simulated solar modulation ΔT_{sol} ≈ 28 %. These values are comparable to experimental results for W-doped VO_2 coatings (Haji et al., 2023). Figure 10 shows the resulting spectra for cold and hot states.

4.3 Proposed Improvements

To enhance system durability and function, future work may explore replacing the outer TiO_2 layers with SiO_2 or Al_2O_3 to improve UV resistance. Adjusting the nanostructure of the TiO_2 surface may also enhance light scattering and heat rejection. Adding a UV-selective filter could minimize unnecessary tint activation during low sunlight. Finally, field testing under Gulf climate conditions would help validate long-term performance and guide further optimization.

5. Conclusion

This study presented a passive photo-thermochromic multilayer coating designed for automotive windshields, using a W-doped VO_2 layer enclosed between TiO_2 films. Both atomistic modelling and optical simulations were used to explore how the proposed structure may respond to temperature and sunlight. The TMM-based optical modelling showed the expected interference behaviour of the multilayer stack and a meaningful difference in visible and solar transmittance between the insulating and metallic states of VO_2. These simulated trends are consistent with the reported characteristics of VO_2-based smart coatings and indicate that the proposed configuration has the potential to reduce glare and solar loading under high-sunlight conditions while maintaining clarity at lower temperatures.

As this work is primarily simulation-driven, the results should be viewed as an early performance indication rather than a substitute for experimental validation. The practical behaviour of the coating will depend on fabrication quality, material purity, and environmental durability, which were outside the scope of this study. Future work may therefore focus on experimentally depositing the multilayer, refining the thicknesses for improved visible-light transmission, and evaluating long-term stability under realistic weather and driving conditions. Exploring alternative outer-layer materials such as SiO_2 or ZnO may further enhance UV resistance and mechanical durability. Overall, the findings suggest that a carefully engineered VO_2-based hybrid structure could serve as a foundation for sensor-free, sunlight-responsive tinting technologies aimed at improving driving comfort and safety in hot climates.

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