

Comparative Review on Smart Window Technologies: Electrochromic, Thermochromic, Photochromic, and Liquid Crystal Windows

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Abstract—Smart window technology has emerged as a pivotal solution in sustainable architecture, offering dynamic modulation of light and heat to improve energy efficiency and occupant comfort. This paper presents an integrated comparative analysis of four major smart window technologies: Electrochromic (EC), Thermochromic (TC), Photochromic (PC), and Liquid Crystal Displays (LCDs). The technologies are evaluated based on their working principles, switching dynamics, energy efficiency, optical performance, limitations, maintenance, and suitability and other architectural applications. Additionally, this paper discusses future trends, including hybrid systems that will further enhance the performance and integration of smart windows in intelligent buildings.

Index Terms—Smart Window, Electrochromic (EC), Thermochromic (TC), Photochromic (PC), and Liquid Crystal Displays (LCDs).

I. INTRODUCTION

As the global demand for energy continues to rise, the building sector remains one of the largest consumers of energy resources, particularly for heating, cooling, and lighting. In response to increasing environmental concerns and the urgent need for sustainable solutions, architects and engineers are progressively adopting smart technologies to enhance building performance. Among these innovations, smart windows have emerged as a transformative advancement in facade design. These dynamic glazing systems offer either passive or active control over the transmission of visible light and solar heat, allowing buildings to adapt to changing environmental conditions throughout the day and across seasons. Smart windows are especially advantageous in regions

exposed to intense solar radiation and in structures characterized by large expanses of glass, where conventional glazing would otherwise result in significant thermal and visual discomfort. By dynamically regulating solar gain and daylight penetration, smart windows not only contribute to substantial energy savings but also promote improved indoor environmental quality and occupant well-being. This paper focuses on a comparative analysis of four major types of smart window technologies—electrochromic (EC), thermochromic (TC), photochromic (PC), and liquid crystal (LC) systems—examining their performance, benefits, and limitations. Through this exploration, the study aims to provide insights into how these adaptive glazing solutions can support the development of future-ready, energy-efficient, and occupant-centred buildings.

II. OVERVIEW OF SMART WINDOW TECHNOLOGIES

A. Electrochromic (EC) Windows

Working Principle:

- Active system: Requires low voltage to trigger ion transfer between transparent electrodes (typically Tungsten Oxide - WO_3 based).
- Voltage induces a reversible optical change by moving ions (e.g., Li^+ or H^+) from cathode to anode across an electrolyte layer, modifying the light transmittance. (El Khattabi et al., 2018)

Structure:

- Multi-layered: Glass / Transparent conductor / EC layer / Electrolyte / EC layer / Transparent conductor / Glass.

- Typically built into double- or triple-glazed units for insulation and electrolyte containment.

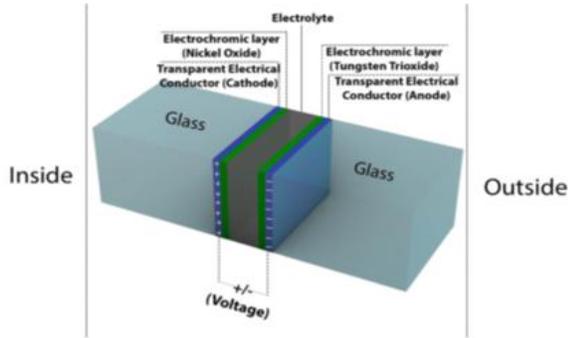


Figure 1- Electrochromic smart window structure, Source- (Rashid Zadeh & Matin, 2023)

Advantages: High energy efficiency, low operating power, long lifespan, adjustable tint.

- Limitations: Slow switching time (7–20 minutes), degradation with cycling, moderate installation cost.
- Applications: Commercial offices, airports, and high-performance facades.

B. Thermochromic (TC) Windows Working Principle:

Principle:

- Passive system: Automatically changes its light and heat transmittance in response to ambient temperature.
- Key material: Vanadium Dioxide (VO_2), which undergoes a phase transition at a certain transition temperature (typically $\sim 68^\circ\text{C}$), affecting its IR reflectance. (Rashid Zadeh & Matin, 2023)

Structure:

- Single coating layer of VO_2 or its doped derivatives (e.g., W-doped VO_2).
- Integrated into double-pane windows, often on the inner side of the outer pane.

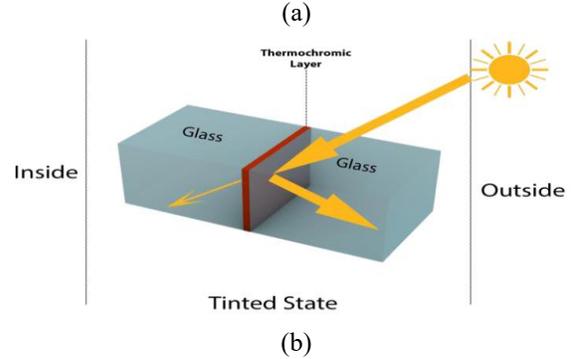
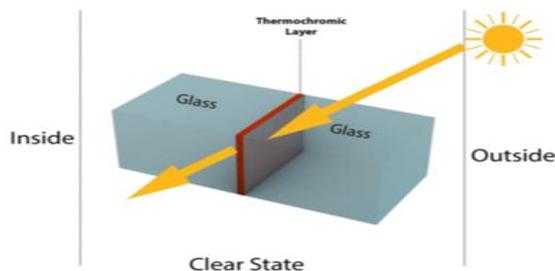


Figure 2- Thermochromic smart window structure (a) Clear state (b) Tinted state

Source- (Rashid Zadeh & Matin, 2023)

Advantages: No electricity required, good for passive solar control, rapid transition (ns–s).

- Limitations: No user control, seasonal performance variation, material aging.
- Applications: Passive buildings, tropical climates, energy-efficient homes.

C. Photochromic (PC) Windows Working Principle

Working Principle

- Photochromic windows utilize materials that undergo reversible color changes when exposed to ultraviolet (UV) light. The most common photochromic material is tungsten trioxide (WO_3), which undergoes a reduction from W^{6+} to W^{5+} upon UV irradiation. This reaction causes the material to darken, reducing light and heat transmission. When the UV source is removed, the material bleaches back to a transparent state, although this reverse process is typically much slower. (Miyazaki et al., 2017)

Mechanism Summary:

- Sunlight exposure \rightarrow UV triggers coloration (darkening due to electron transition in WO_3).
- No light \rightarrow Gradual bleaching (reversal of electron transfer, returning to original transparency).

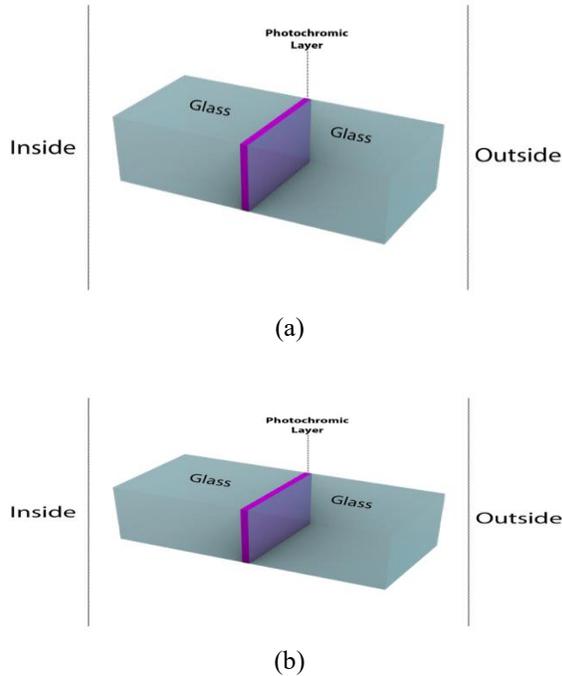


Figure 3- Photochromic smart window structure with (a) double glass and (b) multilayer PC coating
Source- (Rashid Zadeh & Matin, 2023)

Advantages: Passive operation, useful for daylight regulation, glare reduction.

- Limitations: Limited user control, slow responsiveness, susceptible to UV degradation.
- Applications: Skylights, atriums, residential windows, automotive glazing.

D. Liquid Crystal Display (LCD) Windows Working Mechanism:

- Liquid crystal smart windows operate by modulating light transmittance based on the alignment of liquid crystal molecules, which is controlled through applied voltage. (Sung, Lee, & Wu, 2021)

There are two main types:

- Polymer Dispersed Liquid Crystals (PDLC): LC droplets in a polymer matrix scatter light in the off state and become transparent in an electric field. (Sung, Lee, & Wu, 2021)
- Polymer Stabilized Liquid Crystals (PSLC): LC molecules are embedded in a lightly cross-linked polymer network. Unlike PDLCs, PSLCs are transparent in the off state and become opaque when voltage is applied, due to molecular

reorientation that disrupts the uniform alignment. (Sung, Lee, & Wu, 2021)

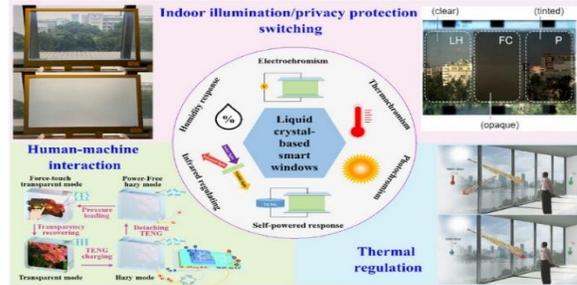


Figure 4 - Schematic illustration of the different LC-based smart window technologies.

Source-Recent Progress in Liquid Crystal-Based Smart Windows: Materials, Structures, and Design - Shen - 2023 - Laser & Photonics Reviews - Wiley Online Library

Key Process:

- No voltage: LC molecules are uniformly aligned—transparent window.
- Voltage ON (~35–40 V): LC molecules misalign—opaque/frosted appearance due to scattering.
- Advantages: Instant switching (ms–s), excellent privacy control, high contrast.
- Limitations: Requires continuous power, limited large-scale application, thermal sensitivity.
- Applications: Office partitions, smart meeting rooms, healthcare facilities.

III. COMPARATIVE PERFORMANCE ANALYSIS

Technology	Switching Speed	Energy Efficiency	User Control	Cost
Electrochromic	Moderate (7–20 min)	High (up to 59%)	Yes	Medium
Thermochromic	Fast (ns–s)	Very High (up to 54%)	No	Low
Photochromic	Slow (variable)	High (20–92%)	No	Low
Liquid Crystal	Instant (Ms–s)	Moderate	Yes	High

Table 1 – Comparative Analysis

IV. OPTICAL AND FUNCTIONAL PERFORMANCE

- EC Windows: Smooth tinting with blue hue, multiple levels of control.
- TC Windows: Passive operation, tint limited to heat levels, limited color variability.
- PC Windows: Moderate transmittance variability, generally neutral color.
- LC Windows: High clarity in transparent state, opacity for privacy, low haze in advanced PDLC systems.

V. MAINTENANCE AND DURABILITY

- EC: Long operational life, minor degradation over time, needs electrical components.
- TC: Stable under optimized doping (e.g., W-VO₂), but can deteriorate under high cycling.
- PC: UV exposure leads to dye fatigue and yellowing.
- LC: Generally robust (>10,000 cycles), but sensitive to extreme humidity and thermal drift.

VI. ARCHITECTURAL APPLICABILITY

- Electrochromic: Best for large external facades requiring adaptive solar control.
- Thermochromic: Ideal for passive structures in climates with consistent solar exposure.
- Photochromic: Limited to aesthetic and daylight control applications.
- Liquid Crystal: Best for interior use and privacy-demanding spaces.

VII. TRENDS AND FUTURE ADVANCEMENTS

- Hybrid Windows: Combining electrochromic with thermochromic/photochromic for dual-mode operation.
- Photovoltaic Integration: Smart windows that self-power via integrated solar cells.
- AI-Controlled Glazing: Responsive systems using environmental data for autonomous operation.

- Material Innovation: New polymers, nanomaterials, and doping techniques to enhance switching speed and durability.

VIII. CONCLUSION

Smart windows are transforming the landscape of sustainable architecture. Electrochromic and thermochromic windows offer the greatest potential for energy savings in hot climates, while liquid crystal systems provide fast, user-friendly solutions for interior applications. Photochromic technologies, though limited by control and durability, still hold aesthetic and passive design value. As technology advances, the integration of smart windows into intelligent, data-driven building systems will be crucial to achieving next-generation energy performance and comfort standards.

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REFERENCES

- [1] El Mehdi El Khattabi, Mohamed Mharzi, Mohammed Zouini and Kęstutis Valančius. (2018). Comparative Study of Various Thermal Analyses of Smart Windows in Cubic Building Design. *Journal of Engineering Science and Technology Review*.
- [2] Guan Fu Sung, Wei Lee and Po-Chang Wu. (2021). Electrically controllable and thermally responsive liquid-crystal smart window. *Polymers*.

- [3] Hidetoshi Miyazaki, Takumi Ishigaki & Toshitaka Ota. (2017). Photochromic Smart Windows Employing WO₃-Based Composite Films. *Journal of Materials Science Research*.
- [4] Zhina Rashidzadeh and Negar Heidari Matin. (2023). A Comparative Study on Smart Windows Focusing on Climate-Based Energy Performance and Users' Comfort Attributes. *Sustainability*.