Smart Glass

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The term “smart window” was coined by Granqvist in 1985. From the early 1980s, smart glazing has been a rapidly developing innovative technology that is aimed to help manage energy transfer through the building’s envelope, evading unnecessary “cooling and heating of indoor air”. The use of smart glass, which helps to regulate the amount of light (and heat) entering a building, is one of the possible ways to reduce energy consumption in buildings while maintaining an appropriate level of comfort for users. Smart glass greatly influences the building envelope performance in (i) thermal management, (ii) daylight harvesting and regulation, (iii) reduction of glare, (iv) maintenance of views, (v) power capture, and finally (vi) activating the envelope as an information display. Some technologies are currently available on the market, although—in light of the many shortcomings of the existing solutions—smart glass is the subject of ongoing “intensive research aimed at improving the technology and its widespread use”.

smart glass smart window electrochromic

1. General Classification

In general, the term “smart glazing” or “smart window” refers to various technological solutions that change light transmission through the material (usually glass). Optical transparency can be altered qualitatively or quantitatively. A qualitative change is made when a transparent glass pane turns into a translucent one (the amount of light does not significantly change, while the light becomes scattered). A quantitative change is made when the amount of light changes, e.g., the transparent panel is dimmed and blocks the portion of incoming radiation (so-called: coloured/darkened state vs. bleached state). Qualitative technologies are used when privacy is required, while quantitative ones are used to protecting buildings from overheating and users from glare. Although the techniques used to achieve such effects have evolved, they generally fall into one of the two categories mentioned above [1]. The layers of smart materials are usually incorporated into the standard insulating glass unit on surface No. 2, which means the internal surface of the external pane.

Nguyen et al. state that “most of (…) smart window research focuses only on modulation within the visible range of the solar radiation (…) However, since nearly 50% of solar energy comes from IR radiation”[2], dynamic modulation of IR radiation should be also included in the review. To quantify and compare solar characteristics of different glass materials (or the same material in a different energy state), the three most popular metrics are used: (i) solar radiation transmittance T_{sol} or (ii) visible (luminous) transmittance T_{vis} and (iii) near-infrared transmittance T_{NIR}. Visible (luminous) transmittance is usually measured at 550–660 nm, while T_{NIR} is usually given for the range of 1000–

1600 nm. Many authors also describe the change in light-transmitting properties by describing the “modulation”. The modulation level is calculated by subtracting the radiation glazing factors for the same smart window at the “high and low potentials”[3], e.g., according to the formulas below:

$$\Delta T_{sol} = T_{sol(bleached)} - T_{sol(coloured)} \tag{1}$$

$$\Delta T_{vis} = T_{vis(bleached)} - T_{vis(coloured)} \tag{2}$$

$$\Delta T_{NIR} = T_{NIR(bleached)} - T_{NIR(coloured)} \tag{3}$$

For the sake of simplicity, the modulation will be used thought the paper to characterise the presented solutions and technologies, however, three different values of the modulation will be given of ΔT_{sol}, ΔT_{vis}, and ΔT_{NIR} (Equations (1) and (3)) as given by the different authors in their papers. However, it must be stated that the authors also provide other metrics, depending on the characteristics of ECD measured.

2. Passive Technologies

The light transmission modulation through smart windows can be achieved by many different technologies. These can be divided into passive and active technologies. Passive technologies are those in which the change in the status of a window (e.g., dimming) results from an external stimulus that could not be influenced (e.g., surrounding parameters) without any external regulation. The best examples of passive technologies are glass with photochromic coatings (glass that dims under the influence of sunlight) or thermochromic coatings (glass that dims under the influence of heat). Some authors—e.g., Park et al.—claim that “passive (technology) is typically more suitable for building application as it is automated and its structures are usually simpler” [4]. Although the passive technologies are not in the focus of the presented paper, it is worth reporting that vanadium dioxide (VO_2) seems to be a promising alternative for developing thermochromic glazings since its “critical” temperature at which the temperature-dependent properties are changed is at approx. 68 °C, not very far from the usual room temperature [5]. The development of thermochromic—based mainly on vanadium dioxide (VO_2)—has led to the design of spectrally selective smart windows which are capable of shielding ΔT_{NIR} = 96.2% of the NIR irradiation and transparency modulation of ΔT_{vis} = 32.9% [6]. In this device, Lee et al. have used tungsten oxide (WO_3)-based EC and vanadium oxide (VO_2)-based TC integrated into a single device. Another interesting thermal-based technology is presented by La et al. in a device that can control both the transmittance of solar radiance with the use of thermally responsive material [7]. The team is using the layer of polyampholyte hydrogel (PAH), which is exposing the phase transition in temperatures between 25 and 55 °C (transparency to opacity). In a device, a layer of PAH is heated by an array of electric heaters made of printed elastomeric composite.

Photochromic windows are also actively researched, with the most recent significant results. In 2019, Timmermans et al. [8] reported dual responsive smart widow regulated both by specific wavelengths of light and electrical triggers. The optical response was due to the content of diarylethene dye incorporated in liquid crystals. Enhanced colouration/bleaching photochromic performance was also reported in 2019 by the team of Li et al. [9]. The device was based on tungsten trioxide (WO_3) that constituted a composite matrix with polyurethane (PU) and polyvinyl pyrrolidone (PVP).

Photo- and thermochromic smart windows are promising technologies, but unfortunately, they do not actively influence the transmission modulation of smart windows. For example, the photochromic glass will be dimmed on a sunny winter day when the greenhouse effect is desired, especially in passive buildings. Similarly, the thermochromic glass will be dimmed on warm days, even if we want to keep the light transmission unchanged, for the reason of, e.g., keeping the proper level of daylight in the room.

An important element of passive technologies is also Phase Change Materials, which react to heat by changing the state from solid (light-scattering) to liquid (light-transmitting). It is important to remember that PCM offers control over the quality of light but is not possible to control on-demand. It was also recently reported by Chou et al. that a passive smart window was proposed with the use of thermotropic hydrogel containing graphene oxide, which changes the state from opaque to transparent under the influence of solar radiation. In this solution, the hydrogel can effectively convert the “photoenergy of sunlight into thermal energy and cause the smart glass to reach an opaque state owing to the increased temperature of the hydrogel heated by solar light” [10]. In 2019, Kim et al. [11] recently presented a device featuring a phase transition of the thermosensitive hydrogel that exhibited optical transition from transparent to opaque state. The phase of the gel was controlled by the film of nanopatterned silver, which effectively generated the heat by the Joule-heating mechanism. **Table 1** features the schematic illustrating all the described technologies:

Table 1. Typological diagram illustrating the described technologies. Diagram by the author.

Type	Stimulus	Technology	Featured Systems
Passive technologies:	Heat—Thermochromic		
	Light—Photochromic		
	Heat—Phase Change Materials		
Active technologies:	Gas—Gasochromic		
	Fluid—Optofluidic glass		
	Electrical current:	Microsystems	
		Microwrinkled Nanometric Films	
		Polymer dispersed liquid crystal	
		Suspended particle devices (SPD)	

Type	Stimulus	Technology	Featured Systems
			Multicolour EC
			Neutral black electrochromism
			Spectrally selective systems NIR/VIS
		Electrochromic:	Electrochromic energy storage window
			Hybrid EC/TC solutions
			EC devices powered by solar cells
			Nanostructures

3. Active Technologies

Active solutions are implemented using several groups of different technologies. They can be divided into several groups, depending on the stimulus that causes the transmission modulation of the smart window.

3.1. Gas

Gasochromic windows (GC) can change their transmittance in the presence of gas—usually diluted hydrogen with some addition of argon—that induces the reduction reaction of the gasochromic layer, resulting in colouring. Two main substances are used: (1) a layer of tungsten trioxide (WO_3) covered by a very thin layer of silver or (2) magnesium yttrium (Mg-Y) alloy. In the first technology, Wittwer et al. produced porous, columnar film of WO_3 by sputtering, and used a low concentration of H_2 to change the colour of gasochromic film. The reverse reaction is obtained with the use of O_2, which bleaches the film to the original transparent state [12]. In the second technology, Liang et al. produced a device with a WO_3 layer, which—after being exposed to diluted H_2 at room temperature—is hydrogenated, which leads to the blue tinting in approx. 5 s (coloured state). The dehydrogenation process is initiated by the use of diluted O_2, which leads to an increase in transmittance (bleaching) [13]. Additionally, magnesium yttrium (Mg-Y) alloys could be also used in the manufacturing of switchable mirrors. The energy efficiency of the latter technology in the building is currently discussed as the gasochromic Mg-Y layer does effectively block the heat, but the corresponding lower solar transmittance reduces daylight availability and the energy consumption for artificial lighting increases.

3.2. Fluid

Optofluidic glass is based on the principle of refractive index matching. The optofluidic window features two layers of transparent material (one of which is roughened/pattered from the inside) and an air cavity between. A roughened surface causes the light rays to reflect and scatter, reducing the light transmittance. When the fluid of specific refractive index matching with the index of the material with roughened/patterned surface is introduced into the cavity, light transmittance is increased. Optofluidic smart windows suffer from many potential maintenance problems, including leakage and the influence of the potential low air temperature (below the freezing point of the liquid), but recently, 3D printing technology allowed for an evident step forward allowing for the manufacture of sealed modules using VeroClear photopolymer. In [14], the team of Wolfe et al. present a novel optofluidic smart glass prototype capable of modulating visible light transmittance (ΔT_{vis}) from 8% to 85% using air (reflective state), water (diffuse transmittance state), and methyl salicylate for specular transmittance. The refractive index of methyl salicylate and photopolymer VeroClear are matched.

Recently, Heiz et al. [15] also presented smart glass that is based on the magneto-active liquid (magnetite nanoparticles in monopropylene glycol) circulating in the cavities/channels parallel to the surface of the glass. The magneto-active liquid is loaded with magnetic nanoparticles, the density of which can be controlled through remote switching in a magnetic particle collector-suspender device in which permanent magnets or electromagnets are used to draw the magnetic nanoparticles from the liquid.

3.3. Electrical Current

Smart windows that are controlled by electrical current include a large group of solutions that will be addressed below. Their common feature is that the change in the state of the window requires the flow of electrons (charged ions)—they are electrically activated. This brief review is given below follows the scale of the technology (from macro, through micro- to nano-solutions).

3.3.1. MEMS-Based Microsystems

In general, micro-blinds made of curling electrodes actuated by electrostatic forces belong to the category of microelectromechanical systems [16]. Microelectromechanical systems (MEMS) include microscopic devices, particularly those with moving parts. Micro-blinds are composed of trapezoid- or rectangle-shaped curling micro-thin metal blinds on a transparent conductive oxide (TCO). In the absence of voltage, the blinds are curled and light passes through. Once the voltage is applied, the difference of potential is created and the electrostatic force stretches the micro blinds so that light is blocked. Most micro shutters are based on standard microelectronic fabrication processes (e.g., e-beam evaporation, magnetron sputtering, optical lithography). The main advantages of micro shutters are fast (virtually instant) switching time, neutral colouration of the transmitted light, low power consumption, and stability for UV and temperature. Few institutions currently work on the development of the micro-blinds including the University of Kassel, Germany [17]; Institut National d’Optique, Canada; and University of Tokyo, Japan [18].

Another type of MEMS is micromirror arrays. Each unit consists of the mirror, the hinge, and the steering mechanism. Micromirror glass is composed of millions of electrostatically actuatable micromirrors that can guide and control light dynamically (typical dimensions are 150 × 400 mm^2). Those systems are used to guide the daylight within the façade, not to block it. Due to the size of the individual mirror, the system is imperceptible for the human eye. The main advantage of the system reported by Hillmer et al. is that the light is reflected, not absorbed, and has low energy consumption, as low as 0.2 mW/m^2 [19].

3.3.2. Microwrinkled Nanometric Films

As was already mentioned above, the roughness of the transparent surface scatters the light. This phenomenon was exploited in the electrically controlled smart glass device that is using transparent soft media with electrically tuneable surface roughness for transparent-to-translucent switching. The system in a “wrinkled” state scatters the light, while in a “stretched” state becomes transparent. The media used as a membrane in the system is a TiO_2 nanometric thin film that is sandwiched between transparent conductive polymers. This system survives 1000 cycles and has a strikingly low power consumption of 0.83 W/m^2 [20].

3.3.3. PDLC (Polymer Dispersed Liquid Crystal)

A smart window based on the Polymer Dispersed Liquid Crystals (PDLCs) features liquid crystal dispersions in a polymer matrix (simply, microdroplets of liquid crystals encapsulated in a polymer), sandwiched between two transparent conducting electrodes. They scatter light in their OFF state because the molecules liquid crystals are randomly arranged, but become transparent when the voltage is applied in their ON state (when the crystals are ordered) [21]. To remain transparent, PDLC smart windows require the continuous application of an electric field, with an average power consumption of 20 W/m^2 as stated by Lampert in [22]. LC molecules embedded in the polymer matrix can be oriented on the demand, thus the transmission could be gradually regulated, as in [23]. This technology is widely used in privacy windows and projection displays because of the fast switching speeds. One of the most widely known commercially available products on the market is Privalite by Saint-Gobain [24].

The latest PDLC technology includes the use of membranes containing liquid crystals with the parameters of an opaque OFF state with a T_{OFF} = 0.5%, and a transparent ON state with a T_{ON} = 65% (difficult to translate to ΔT_{vis} as the haze is described) when the system is switched on, as presented by De Filpo et al [25]. Liquid crystals and polymers with other additives and other forms are also studied. Kim et al. solved the dye contamination problems by encapsulating the dye in monodispersed capsules. Using this technology, a fabricated “dye-doped PDLC had a contrast ratio of >120 at 600 nm” [26]. Although PDLC systems are mainly used for privacy purposes, they can also achieve energy savings. Alghamdi et al. recently reported that a system comprising of sensors with an Arduino to control the percentage PDLC glass transparency produced 39% in energy savings compared to the standard systems in a hot climate [27]. Sol et al. recently reported a smart window featuring liquid crystalline luminescent solar concentrator that allows switching the window between three states: “coloured” for increased light absorption, “light” for transparency (5% of haze), and “scattering” for diffuse transmission of light (66% of haze). In the LSC system, luminescent molecules embedded in a polymer absorb light and reemit downshifted spectrum that is channelled by total internal reflection to the edge of the device, where it is collected by PV cells [28].

3.3.4. SPD Windows

Suspended particle devices (SPD) smart windows work on a similar principle to PDLC, but instead of liquid crystal, they use a suspension of fine, strongly absorbing particles. In the OFF state, the particles are randomly arranged and block the passage of the light. When the voltage is applied in the ON state, the particles align to let the light through. SPD device requires approx. 5 watts per m^2 to remain transparent, as reported by Schwarz [29]. Light transmission values range from about 64–80% in the clear state to 0.5–12% in the dark state [30] as reported by Ghosh. However, it must be noted that due to the number of technological problems, stability, and particle settings, the development of suspended particle devices has been recently slowed. International scientific databases show only less than 10 reports submitted in the years 2015–2020.

The overview of the presented technologies is summarised in **Table 2**.

Table 2. The comparison of the performance of non-electrochromic devices, including the technologies, where the data are available.

No.	Team	Year	Type	ΔT_{sol}	ΔT_{vis}	Remarks
1	Wittwer et al.	2004	Active gasochromic	71%	72%	Switching from transparent to mirror state
2	Liang et al.	2019	Active gasochromic	42%	n/a	
3	Wolfe et al.	2018	Optofluidic	n/a	77%	Clear to foggy
4	Heiz et al.	2017	Magneto-Active Liquid	95%	n/a	Magnetic particles in liquid
5	Hillmer et al.	2018	Microelectromechanical	n/a	n/a	Micromirrors. The team only measured a temperature build-up in the room.
6	Mori et al.	2016	Electrostatic	n/a	17%	Micro blinds
7	Shrestha et al.	2018	Microwrinkled TiO_2 Films	n/a	79.2% haze	Transparent to translucent switching
8	Lampert	1998	PDLC	n/a	40% haze	
9	Lampert	2004	PDLC	60%	57% haze	
10	Murray et al.	2016	PDLC	n/a	25–29% haze	
11	De Filpo et al.	2019	PDLC	n/a	64% haze	
12	Sol et al.	2017	PDLC	n/a	61%	

No.	Team	Year	Type	ΔT_{sol}	ΔT_{vis}	Remarks
					haze	
13	Ghosh	2017	SPD	46%	n/a	

3.3.5. ECDs

Electrochromic windows are—according to the survey performed by the author—the leading branch in smart window applications, constituting the majority of search results in international science databases in the years 2015–2020. The technology has been known since the 1960s when S.K. Deb published important work on the characterisation of molybdenum and tungsten oxide thin films [31]. He had originally observed that some types of metal oxides can change the colour to blue (and brown) due to the reduction reaction and become uncoloured again due to the oxidation reaction.

Electrochromic devices (ECDs), in general, are used for applications ranging from commercialised smart window glasses, goggles, and auto-dimming rear-view mirrors [32]. Recent achievements in electrochromic smart windows technology call for a review study of the most recent concepts that are used to obtain hitherto impossible results and are studied in detail in the following section.

3.3.5.1 Switching Mechanism

Electrochromism is a reversible chemical phenomenon, where the electrochromic material changes its colour when the voltage is applied. As Kraft writes, the substances, “which change from an uncoloured oxidised state to a coloured reduced state by electrochemical reduction are called cathodic electrochromic, whereas compounds which change from an uncoloured reduced to a coloured oxidised state are called anodic electrochromic compounds” [17]. EC windows operate on the principle of the reversible electrochemical intercalation of positive ions (e.g., H^+, Li^+, Na^+) accompanying the insertion of charge balancing electrons into the multivalent transition metal oxides (e.g., WO_3, NiO, IrO, MoO_3, V_2O_5) [27]. The basic chemical reaction featuring the most popular cathodic electrochromic compound WO_3 transforming from transparent to blue is given below:

$$\mathrm{M}x\mathrm{WO3} \rightleftarrows \mathrm{WO_3} + xe^- + x\mathrm{M}^+ \quad x \le 0.3 \tag{4}$$

while nickel oxide (NiO) can be coloured anodically to a brown colour in a reaction of

$$\mathrm{LiNiO} \rightleftarrows \mathrm{NiO} + \mathrm{Li}^+ + e^- \tag{5}$$

However, other transition metal oxides such as Co_3O_4, MoO_3, V_2O_5, TiO_2 also exhibit electrochromic properties [52,53]. Prussian blue (iron ferrocyanide) – originally reported by Mortimer [54] – also currently is studied as a material presenting some electrochromic behaviour [55]. Recently, polystyrene sulfonate (PEDOT:PSS) were researched as exhibiting electrochromic properties, as well as presented by Singh [51].

3.3.5.2 Electrochromic Device Architecture

Electrochromic devices typically consist of five thin layers that are located (sandwiched) between two panes of glass or flexible polyester foil: two external layers of transparent conductive films (usually indium tin oxide, ITO) and the counter electrode (Ni-oxide-based film), electrolyte, and electrochromic electrode in between (W-oxide-based film). The counter electrode is used for ion storage, the electrolyte for conducting ions, and the electrochromic electrode for attracting ions. When the electrical current is applied, the ions stored in the counter electrode (bleached state) migrate through the electrolyte to the electrochromic electrode, resulting in the colouration (coloured state). The mobile ions should be small. Hydrogen protons (H^+) or lithium (Li^+) ions are commonly used [18]. EC device can be considered as an electrical battery in which the optical absorption is related to its charge; therefore, the crucial component of an ECD is an electrolyte, which can be liquid, gel, or solid, as addressed by Cannavale et al [56]. The most popular ECD architecture is pictured in **Figure 1**.

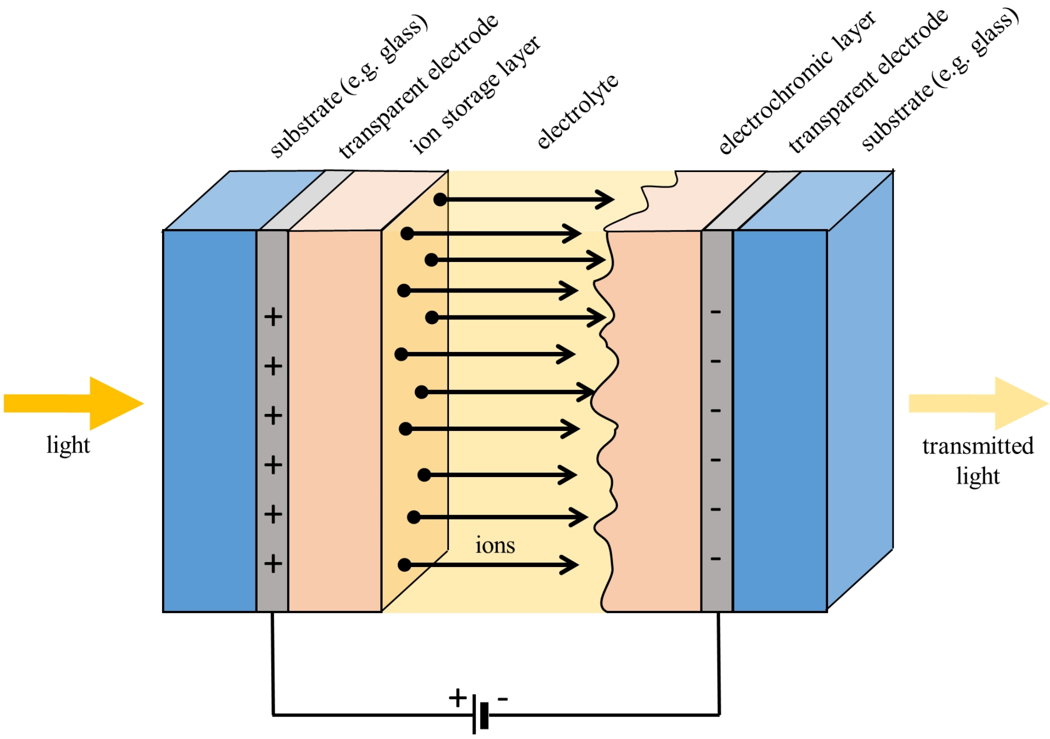

Figure 1. The most popular ECD architecture. Diagram by the author.

3.3.5.3 Most Recent Concepts in EC Smart Windows

As is said above, EC technologies suffer from many problems that are currently being addressed by many research teams tackling the challenges of the EC windows. The concepts of the most recent solutions are Multicolour EC, Neutral black electrochromism, Spectrally selective systems NIR/VIS, Electrochromic energy storage window, Hybrid EC/TC solutions, EC devices powered by solar cells, the application of nanostructures in ECw.

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