

Review

Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review

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ARTICLE INFO

Article history:

Received 11 June 2009

Accepted 15 August 2009

Available online 1 October 2009

Keywords:

Transparent conductor

Smart window

Electrochromic window

Gasochromic window

Liquid crystal window

Suspended-particle window

Electrophoretic window

Daylight control

Solar energy control

ABSTRACT

A survey on prototype and currently commercial dynamic tintable smart windows has been carried out. The technologies of electrochromic, gasochromic, liquid crystal and electrophoretic or suspended-particle devices were examined and compared for dynamic daylight and solar energy control in buildings. Presently, state-of-the art commercial electrochromic windows seem most promising to reduce cooling loads, heating loads and lighting energy in buildings, where they have been found most reliable and able to modulate the transmittance up to 68% of the total solar spectrum. Their efficiency has already been proven in hot Californian climates, but more research is necessary to validate the products for colder climates, and to improve furthermore the commercial products in order to control the indoor climate in a more energy efficient way by reducing both heating and cooling loads.

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1. Introduction

Windows are often regarded as a less energy efficient building component with a larger maintenance requirement. Nevertheless, their technology has grown by leaps over the last several years. A new class of windows promises to set the technology bar even higher. Dynamic tintable or the so-called smart windows, where an example is shown in Fig. 1, can change properties such as the solar factor and the transmission of radiation in the solar spectrum in response to an electric current or to the changing environmental conditions themselves. The application of such windows may lead towards a drastic reduction of the energy consumption of highly glazed buildings by reducing cooling loads, heating loads and the demand for electric lighting.

Various techniques are known to derive switchable windows. However, taking into account the specific properties of window glazing in buildings, one strict rule has to be reckoned with: A transparent mode of the glazing has to be possible. Presently, three different technologies with external triggering signal are commonly known for this purpose and start to be available on the market: Chromic materials, liquid crystals and electrophoretic or suspended-particle devices. Here, the chromic devices may be divided in four categories, i.e. electrochromic, gasochromic, photochromic and thermochromic devices, where the last two possibilities will respond automatically to, respectively, changes in light and temperature. However, because one can not control the outdoor weather conditions and hence neither the properties of the photo- and thermochromic windows, they will be mostly neglected in this review.

Smart windows are to be judged on several specific factors. Of most importance is their transmittance modulation range in the

visible and whole solar spectrum. The modulation range is often expressed for a single wavelength in literature, but this gives little or no information on the overall performance of the smart device. Secondly, the expected lifetime and number of achieved cycles without or only minor degradation are of uttermost importance. Thirdly, the switching time for colouration and bleaching is important, mostly expressed as the time necessary to reach 90% of its maximum modulation range. The magnitude of the switching time is strongly connected to the size of the device, as large devices tend to have long switching times. Furthermore, the achieved window size, the total energy consumption, the operating voltage and the operating temperature range are of importance.

Within this work, a review is given on the current technology of these smart window technologies. Main questions within this review are *how do different devices obtain their dynamic tintable properties, which possibilities are available today to adapt the performance of these devices and how do the different technologies perform under laboratory conditions?* However, there is no aim within this review to give a historical overview on the subject. The real focus in this study lies within commercial available smart windows. A survey is performed on what types of smart windows are currently available on the market and their properties and potential for daylight and solar energy control in buildings. The aim is to find out which technologies are of most interest for the mentioned building applications and which are most developed today.

2. Transparent conductors

Before we look closer on the properties of the different types of smart windows, transparent conductors (TC) have to be treated.

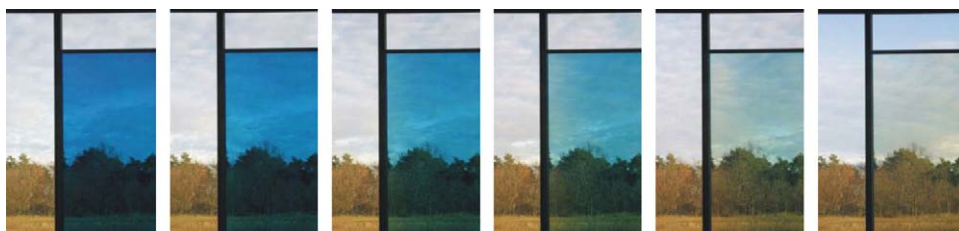


Fig. 1. Switching sequence of an electrochromic laminated glass [46].

TCs are a major issue for all electrically activated devices because of the need for a high-quality TC and their costs. TCs need a high transparency in order to let the active part of the smart windows regulate as much as possible. Furthermore, the TCs need a high electronic conductivity to provide a low voltage drop along the conductor surface. For the field effect devices, i.e. liquid crystals and electrophoretics or dispersed particles (see Chs. 5–6), the need for the lowest resistivity for large areas is less than for electrochromics [77].

The most widely used transparent conductor in all kind of devices, e.g. touch screens, is tin-doped indium oxide $\text{In}_2\text{O}_3(\text{Sn})$ (ITO), which may be replaced by heavily doped conductors such as $\text{SnO}_2:\text{F}$ (FTO), $\text{ZnO}:\text{Al}$ or $\text{ZnO}:\text{Ga}$, while many more are available as shown by Granqvist [52]. However, ITO is in short supply. In fact, one predicts that we could run out of indium, a silvery metal produced as a by-product of zinc mining, in the next 10 years. The price of the metal has raised from around US \$100/kg to nearly \$1000 in the past 6 years. Several new promising TCs related to energy applications are offered in the last decade:

- i. Based on current technology, PEDOT or poly(3,4-ethylene-dioxythiophene) seems the best alternative as TC [54,55,124]. The polymer combines a transmittance above 0.90 with an electrical resistivity currently below $400\ \Omega/\square$ for commercial products. However, long-term stability remains a problem: PEDOT degrades over time if exposed to light or heat.
- ii. Carbon nanotubes (CNT) layers seem more promising compared with PEDOT, but are far from large-area applications [30,135]. Carbon nanotube layers have a high transparency in the visible and IR spectrum and sheet resistances around $10^{-4}\ \Omega/\square$ have been measured. The sheet resistance increases by increasing transmittance. CNT networks are p-type conductors, whereas traditional transparent conductors are exclusively n-type. The availability of a p-type transparent conductor could lead to new cell designs that simplify manufacturing and improve efficiency: They are easier and cheaper than ITO to deposit on glass and plastic surfaces, since they can be formed into a solution, compared with ITO which has to be sputtered onto a surface in a vacuum.
- iii. A third new material is $12\text{CaO} \cdot 7\text{Al}_2\text{O}_3$, often denoted as C12A7 [57], which itself is an electrochromic material and turns green by a process involving $\text{H}^0 \rightarrow \text{H}^+ + \text{e}^-$ after incorporation of hydrogen inside the cages. However, even if the C12A7 type of TCs is very interesting, the current properties are far from possible applications in electrochromic windows.

A complete overview on the market of ITO and alternative transparent conductors is out of the scope of this work, but can be found in NanoMarkets [98]. One may conclude that ITO will far from disappear because too many products rely on it, but the future for high-performing transparent conductors in electronic devices as well as smart windows may currently lies in CNTs.

3. Electrochromic windows

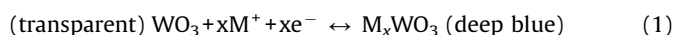
Electrochromism is the property of a device to change its optical properties reversibly if an external potential is applied, associated with ion insertion and extraction processes. The electrochromic device mostly consists of several layers. The basis is a glass or plastic covered by a transparent conducting film, i.e. mostly ITO (see Ch.2), on which one (or multiple) cathodic electroactive layer(s) are affixed. These are followed by a layer of ion conductor, on its turn followed by an ion-storage film or one (or multiple) complimentary anodic electroactive layers and another transparent conducting film.

The electroactive layers, often denoted as *electrochromics*, change their optical properties by switching between their oxidized and reduced form. Electrochromism may be seen as a device characteristic instead of material property. Most favourable are electrochromics that are reflecting in their coloured state instead of absorbing, but this has been found very difficult and most electrochromics are absorbing. By combining different type of electrochromics, ion-storage films and ion conductors, different properties can be obtained for the device, where the modulation range, durability and switching speeds can be optimized.

Many of these electrochromics are well-known today [49]. Most important are the metal oxides, of which tungsten oxide is the most well-known, but also electrochromic polymers are applied in electrochromic windows and devices.

3.1. Tungsten oxide

The electrochromic phenomenon of materials was originally discovered in tungsten oxide WO_3 thin films, and remains until now the most promising, most studied and most applied electrochromic material in EC windows and devices. Electrochromism of tungsten oxide is a complex phenomenon and is still not yet completely understood, but it may and can be represented by the simple reaction



where M^+ can be H^+ , Li^+ , Na^+ or K^+ , $0 < x < 1$ and where e^- are denoting electrons. WO_3 turns blue, while doping the oxide with molybdenum Mo provides colour neutrality. Depending on the crystallinity of the tungsten layer, tungsten oxide obtains its modulation due to reflectance or absorbance. One example of transmittance regulation in an electrochromic window incorporating WO_3 is shown in Fig. 2.

Extensive reviews on tungsten oxide films have been written previously, where 'Case study on tungsten oxide' in Granqvist [48] and its completion with Granqvist [50], and 'Colouration of tungsten oxide films: A model for optically active coatings' by Bange [11] are among the most comprehensive. Also recent possibilities have been expressed [26,45] and we would like to refer to these works for more detailed information on the colouration mechanisms of tungsten oxide.

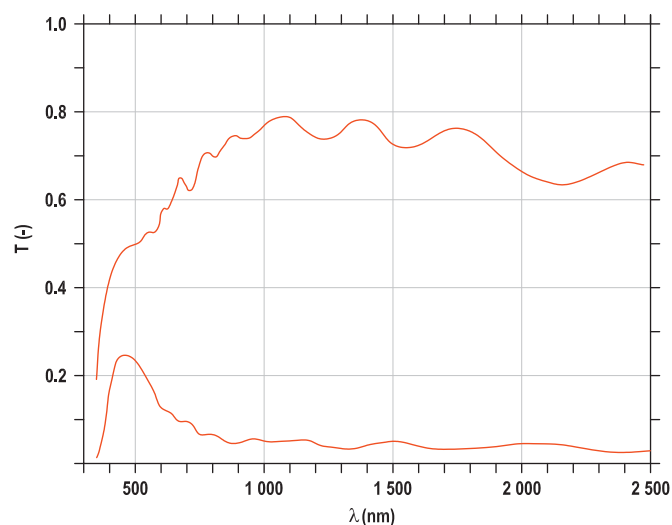


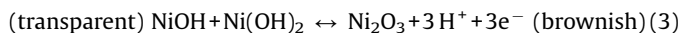
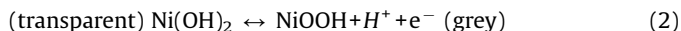
Fig. 2. Spectral transmittance vs. wavelength for a smart window (i.e. $\text{ITO}|\text{WO}_3|-\text{LiNbO}_3|\text{V}_2\text{O}_5|\text{In}_2\text{O}_3$) (redrawn from [47]).

3.2. Other electrochromic metal oxides

Many other electrochromic metal oxides are known besides WO_3 and applied in prototype electrochromic windows [53], e.g. Bi_2O_3 , CeO_2 , CoO , CuO , FeOOH , Fe_2O_3 , Fe_3O_4 , FeO , MnO_2 , MoO_3 , P_2O_{5-y} , RhO_3 , RuO_2 , SnO_2 , Ta_2O_5 , TiO_2 and V_2O_5 , but most interest lately goes towards nickel oxide $\text{Ni}^{\text{II}}\text{O}_{(1-y)}\text{H}_2$, iridium dioxide IrO_2 and niobium pentoxide Nb_2O_5 . Several of these oxides, besides WO_3 , have been studied by Lampert [74,76], e.g. various hydrated nickel oxide films [75,146,147].

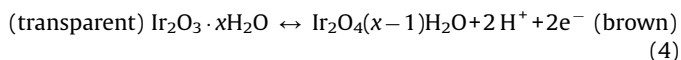
3.2.1. Nickel oxide

Films based on NiO have enjoyed much interest lately because they combine a reasonable cost with excellent electrochromic properties, which even can be improved by mixing NiO with wide band gap oxides such as MgO or Al_2O_3 [4–6,36,61,90,92,111,138,149,150]. NiO:X , i.e. where X is Mg, Al, Si, V, Zr, Nb, Ag, Ta, Li, Al or B, has been found complementary with $\text{WO}_3\text{:X}$ in the visible and near IR: pairing them in a complete device results in a very dark colour neutral system [95]. The main effect of electrochromic effect takes place in the UV and VIS spectra and reaches a very high colouration efficiency between $100\text{ cm}^2/\text{C}$ at 340 nm and $25\text{ cm}^2/\text{C}$ at 800 nm . A 200 nm layer has been defined by a T_{vis} of 0.80–0.10 at an oxygen concentration somewhat below 1.5%.



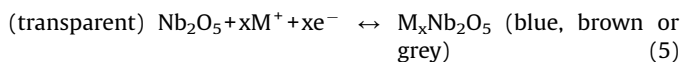
3.2.2. Iridium oxide

Also films based on IrO_2 and Ir_2O_3 have enjoyed an increased interest lately [8–10,69,100]. While IrO_2 -based films are excessively expensive, good electrochromic properties are obtained after dilution with the much cheaper Ta_2O_5 .



3.2.3. Niobium oxide

The interest in niobium pentoxide Nb_2O_5 has increased in the last decade because of its promising electrochromic properties [58,93,96,97,109,110,116]. Pure Nb_2O_5 and doped $\text{Nb}_2\text{O}_5\text{:X}$, i.e. where X is Sn, Zr, Ti, Li, Mo, WO_3 or TiO_2 , layers change colour by insertion of H^+ or Li^+ ions from transparent to brown, blue or grey depending on the crystallinity of the layer.



Undoped Nb_2O_5 has a high transmittance of 0.80–0.92 in the visible region for the bleached state (see Fig. 3) and transmittances between 0.10 and 0.30 are obtained in the coloured state, with relatively slow colouring and bleaching times. The disadvantage of the Nb_2O_5 layers is their small colouration efficiency CE of about $12\text{--}27\text{ cm}^2/\text{C}$ compared with the CE of $37\text{--}50\text{ cm}^2/\text{C}$ of tungsten oxide.

Lithiated niobium oxide $\text{Li}_x\text{Nb}_2\text{O}_5$ films exhibits a much higher electrochromic reversibility, where bleaching is accomplished after a few seconds, while colouring times remain the same.

3.2.4. Other inorganic electrochromics

Not all inorganic electrochromics are metal oxides. One of them is the widely studied Prussian blue (PB), i.e. $\text{K}_3\text{Fe}(\text{CN})_6$, [1,23,59,63–68] which colour reaction may be described as



where M^+ is a cation, e.g. K^+ . PB is the prototype of a polynuclear transition metal hexacyanometallate with the general formula

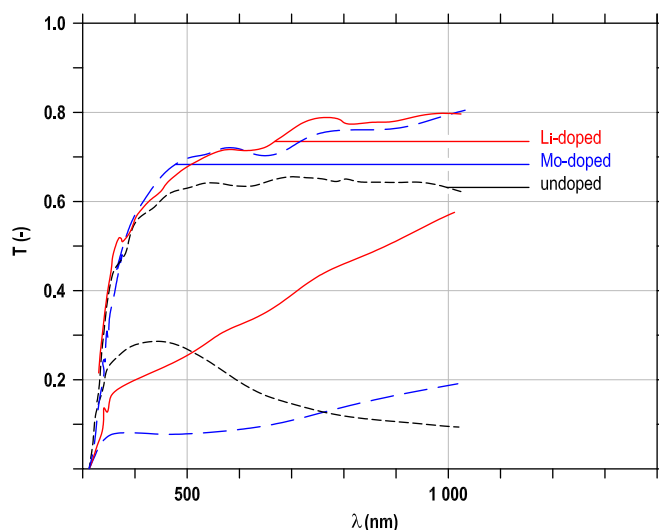


Fig. 3. Transmittance spectra of undoped and Mo- and Li-doped $\text{Nb}_2\text{O}_5\text{:X}$ sol-gel double layers on K-glass in the coloured and bleached state at -2.2 and $+1\text{ V}$ (redrawn from [58]).

$\text{M}'\text{k}[\text{M}''(\text{CN})_6]_l$ (l, k integers), where M' and M'' are transition metals with different formal oxidation numbers [127]. The electrochemical reduction and oxidation of PB can lead to Prussian White and Prussian Green, respectively. A cycle life of 10^5 cycles has been found in solutions of pH 2–3, while also depositing a PB film on a polyaniline coating yields a superior cycling lifetime compared with a PB film deposited directly onto a platinum or ITO substrate. Besides, a symbiotic relationship between polyaniline and PB is found resulting in enhanced colouration [63–68].

Transmittance spectra of pure Prussian Blue have been studied by Jelle et al. [66] with the 'hole method' in a solid state device containing tungsten oxide, polyaniline and PB. Here, the transmittance spectra of a single layer EC at various colouration stages have been measured and calculated by comparing the transmittance spectra of different devices with holes in an electrochromic layer with the reference device without electrochromic layers.

3.3. Polymer electrochromics

Besides the oxide films there are also organic films available with EC properties, but most of them show UV degradation and are hence less likely for possible energy-related applications in exterior smart glazing. Many different polymers have been incorporated in prototype EC devices, e.g. poly- and monomeric pyrrole, viologens, 4,4'-diaminodiphenyl sulfone, poly(3-methylthiophene) or diclofenac, but most interest lately goes towards polyaniline (PANI) and poly(3,4-ethylene-dioxythiophene) (PEDOT). As for the inorganic electrochromic materials, the electrochromic polymers do also need to have a transparent state for application in smart windows.

3.3.1. Polyaniline

Polyaniline is a conducting polymer which may undergo colour changes from a transparent state to violet by both a redox process and proton doping. A simplified formula for PANI consisting of reduced and oxidized units can be written as $[(-\text{B}-\text{N}(\text{H})-\text{B}-\text{N}(\text{H})-)_x(-\text{B}-\text{N}=\text{Q}=\text{N}-)_{1-x}]_y$ with benzenoid and quinoid units (see Fig. 4). This conversion of benzenoid units into quinoid units results in a typical absorption peak around $600\text{--}700\text{ nm}$. PANI is one of the most extensively researched electrochromic material till date, owing to its good electrochemical cycling stability in

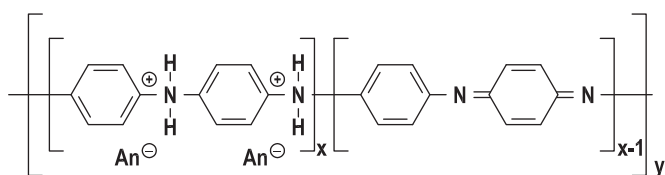


Fig. 4. A simplified formula for PANI consisting of reduced and oxidized units with benzenoid (B) and quinoid (Q) units that may be written as $[(\text{--B--N(H)--B--N(H)--})_x (\text{--B--N=Q--N--})_{x-1}]_y$ (redrawn from [136]).

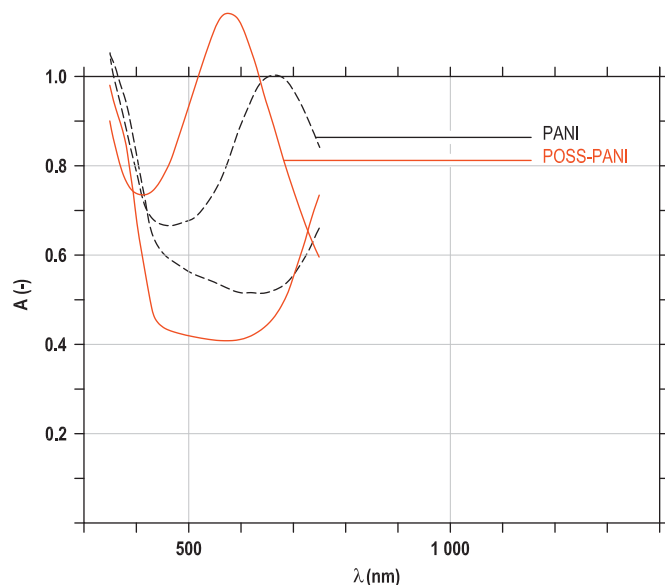


Fig. 5. UV-vis absorbance spectra of the complementary EC device PET|ITO|PANI|Electrolyte|WO₃|ITO|PET and PET|ITO|POSS-PANI|Electrolyte|WO₃|ITO|PET switched at 2.0 and -2.0 V. (redrawn from [151]).

non-aqueous electrolytes above 10^6 cycles, its low cost and ease of processing by electrodeposition or liquid casting techniques. High colour contrast is usually observed for thick films ($> 1 \mu\text{m}$) of PANI but it is achieved at the expense of switching speed [27].

Recently, a new class of hybrid polymers has been developed at the Nanyang Technical University of Singapore [141,142,151] based on aniline, with a 40% enhancement in electrochromic contrast at their λ_{max} compared with PANI (see Fig. 5) because of more accessible doping sites and with increased electrochemical stability.

The polymer polyaniline-tethered polyhedral oligomeric silsesquioxane (POSS-PANI) was synthesized through copolymerization of aniline with octa(aminophenyl) silsesquioxane (OAPS) in the presence of dodecylbenzene sulphonic acid (DBSA) or poly(4-styrene sulfonic acid) (PSS) as dopant, with a feed molar ratio of OAPS to aniline of 0.5/99.5. A loosely-packed structure is formed because of covalent binding of the PANI chains to the POSS nanocages, creating a nano-porous structure and allowing easy ion movement during redox switching, proven by an increased ionic conductivity by one order of magnitude and a decrease of up to 2 orders of magnitude compared with PANI. When switched from -2.0 to +2.0 V, 0.5% POSS-PANI|PSS has a total change in absorbance ΔA of 0.66 at λ_{max} compared with 0.44 for PANI/PSS. The coloration time of POSS-PANI|PSS has been found approximately equal to that of PANI/PSS, but the bleaching times have been found slightly shorter.

3.3.2. Poly(3,4-ethylene-dioxythiophene)

Electrochromic applications based on π -type polymers have also drawn a lot of attention due to their ease of colouring, high electrochromic contrast and fast response times, of which poly(3,4-ethylene-dioxythiophene) (PEDOT) and its derivatives are most researched. PEDOT switches from blue in the neutral state to transparent in the oxidized state, but has a rather weak electrochromic contrast. As far as known by the authors, a maximum transmittance change ΔT_{610} of 0.65 has been measured [72].

Table 1

Data for WO₃-based electrochromic devices found in literature showing materials, sample size, modulation range, the performed number of colouring/bleaching cycles and the switching time for colouration and bleaching $\tau_{c/b}$.

	Size (cm ²)	$T(-)$	cycles	$\tau_{c/b}$ (s)	Reference
WO₃-based construction					
G ITO WO ₃ PVB:LiClO ₄ CeTiO _x ITO G	100	$T_{\text{sol}} 0.73-0.045$ $T_{\text{vis}} 0.81-0.07$	16×10^3	60	Schlotter et al. [120]
WO₃/NiO-based construction					
G ITO WO ₃ PMMA-PC-Li ⁺ NiO ITO G	–	$T_{600} 0.78-0.31$	10^4	–	Lechner and Thomas [80]
G ITO WO ₃ ZrP·xH ₂ O ZrO ₂ NiO ITO G	25	$T_{\text{vis}} 0.74-0.38$ $T_{\text{sol}} 0.53-0.25$	–	60	Azens et al. [7]
G SnO ₂ WO ₃ PVDF-Li ⁺ NiO:Li SnO ₂ G	7	$T_{\text{vis}} 0.75-0.02$	–	–	Karlsson and Roos [70]
G ITO WO ₃ Ta ₂ O ₅ NiO ITO G	2400	$T_{\text{vis}} 0.73-0.18$ $T_{\text{sol}} 0.55-0.11$	10^5	–	Michalak et al. [95]
G SnO ₂ WO ₃ PEO/PEGMA:Li ⁺ NiO:Li SnO ₂ G	144	$T_{\text{vis}} 0.70-0.27$	–	120	Penissi et al. [112]
G P ITO WO ₃ ZrP ZrO ₂ NiO ITO G	20	$T_{\text{vis}} 0.75-0.14$	10^3	180/60	Kullman et al. [73]
P ITO WO ₃ PMMA-PPG-Li ⁺ NiO ITO P	220	$T_{550} 0.70-0.35$	5×10^3	200	Granqvist et al. [51]
G FTO WO ₃ P-3 NiO FTO G	12.5	$T_{\text{vis}} 0.58-0.06$	10^3	2	Zelazowska [150]
WO₃/IrO₂-based construction					
G P ITO WO ₃ Ta ₂ O ₅ IrO ₂ ITO	30	$T_{550} 0.70-0.18$	3.5×10^4	–	O'Brien et al. [101]
WO₃/Polymer-based construction					
G ITO WO ₃ PAMPS PANI ITO G	2	$T_{\text{sol}} 0.74-0.35$	–	11/11	Jelle and Hagen [64]
G ITO WO ₃ PAMPS PB PANI ITO G	2	$T_{\text{sol}} 0.73-0.23$	4×10^3	34/23	Jelle and Hagen [64]
G ITO WO ₃ PAMPS PB PANI ITO G (another version)	2.8	$T_{\text{sol}} 0.64-0.08$	–	300/100	Jelle and Hagen [65]
G SnO ₂ WO ₃ PVSA:PVP:H ⁺ PB SnO ₂ G	155	$T_{550} 0.72-0.06$	2×10^4	30	Ho [59]
G ITO WO ₃ PAMPS:L PANI-CSA AR ZnSe AR	–	$R_{1200} 0.65-0.22$	900	9	Topart and Hourquebie [134]
P ITO WO ₃ :H ₂ O PVDF-HFP-Li ⁺ PANI ITO P	–	$T_{800} 0.12-0.02$	–	–	Marcel and Tarascon [94]

G denotes glass, P denotes polymer and the subscript for T signifies the wavelength in nm for which the values have been obtained.

3.4. All-solid-state electrochromic windows and devices

Many of the properties obtained for single electrochromic materials are obtained by analysing the potentiostatic response of a thin film while immersed in an electrolyte. By combining different types of these electrochromics, ion-storage films and ion conductors, different properties can be obtained for the device, where the modulation range, durability and switching speeds can be optimized. However, a viable electrochromic window (ECW) is more than the sum of its components. It represents these parts assembled and working together.

For future applications, one must focus on large-area windows and cyclability, two factors that are mostly neglected in scientific literature.

A division in electrochromics has been made as organic and inorganic materials, but this division is not possible for ECWs because many use both organic and inorganic electrochromic materials within the same device. More appropriate here is to make a division between devices containing tungsten oxide and devices which do not. Tungsten oxide WO_3 is widely known for its good electrochromic properties and stability resulting in many tungsten-based prototype and commercial EC windows and devices, while tungsten-free electrochromic devices are *rather* rare.

3.4.1. Tungsten-based electrochromic windows

Tungsten oxide WO_3 is used in a wide range of electrochromic devices. A selection is given on WO_3 -based electrochromic windows and their properties in Table 1 based on the previous mentioned electrochromics, but many more devices can be found in literature.

So far, the largest modulation ranges found in literature are from WO_3 -based devices, but modulations ranges higher than 0.50 in T_{sol} or T_{vis} are rare. A transmittance modulation of 0.56 is achieved by Jelle and Hagen [65] for a $\text{WO}_3/\text{PB}/\text{PANI}$ device for the complete solar spectrum, while a range of 0.55 for the visible spectrum has been achieved by Nagai et al. [152] for a relatively large WO_3/NiO device of $40 \times 60 \text{ cm}^2$. However, these values are widely surpassed by the values retrieved by Schlotter et al. [120] with a single active but thicker WO_3 layer resulting in a modulation range of 0.74 and 0.68 for T_{vis} and T_{sol} , respectively (e.g. Fig. 6). Degradation occurs *rather* fast in this last model, but the resulting modulation ranges after 16,000 cycles remain very high compared with other electrochromic devices.

3.4.2. Non-tungsten-based electrochromic windows

Compared with the amount of published tungsten-based smart windows, tungstenless devices are rare. Most of them concern of niobiumoxide-based electrochromic device and all-polymer devices. However, only small devices have been found and the cyclability is *rather* poor for the polymer devices compared with earlier stated tungsten devices.

A selection is given on non-tungsten electrochromic windows and their properties in Table 2 based on the previous mentioned electrochromics, but many more devices can be found in literature.

3.4.3. Photovoltaic integrated electrochromic devices

EC windows with no external wiring are most desirable in the building industry. Here, an integrated photovoltaic-powered window is an obvious choice, particularly because PV and EC technology have compatible operational characteristics (see Table 3).

Self-powered photovoltaic electrochromic devices have been built by the *National Renewable Energy Laboratory* of Golden, USA. The development of a side-by-side PV-powered ECW [17,18] resulted in the fabrication of a monolithic a-SiC:H PV-powered ECW of 16 cm^2 [25,26,34,35] and monolithic dye- TiO_2 PV-powered ECWs up to 25 cm^2 [16,56,113]. Here, the main concerns for future

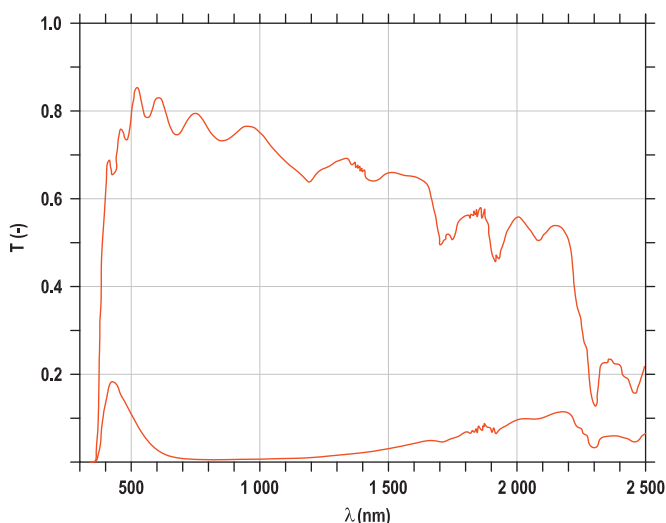


Fig. 6. Spectral transmittance of a WO_3 -based electrochromic window (redrawn from [120]).

Table 2
Data for non-tungsten electrochromic devices found in literature showing materials, sample size, modulation range, the performed number of cycles and the switching time for colouration and bleaching $\tau_{c/b}$.

	Size (cm^2)	T (–)	cycles	$\tau_{c/b}$ (s)	Reference
<i>Nb₂O₅-based construction</i>					
G SnO_2 Nb_2O_5 :Li Ormolite-Li ⁺ SnO_2 :Sb:Mo SnO_2 G	9	T_{550} 0.70–0.20	–	120	Orel et al. [106]
G FTO Nb_2O_5 :Li PC:LiClO ₄ (CeO ₂) _x (TiO ₂) _{1-x} TFO G	50	ΔT_{0-1000} 0.14	2×10^3	–	Heusing et al. [58]
G FTO Nb_2O_5 :Mo PC:LiClO ₄ (CeO ₂) _x (TiO ₂) _{1-x} TFO G	1 200	T_{550} 0.60–0.25	55×10^3	180	Heusing et al. [58]
<i>Polymer-based construction</i>					
G ITO PEDOT PC PANI ITO G	4	T_{570} 0.58–0.14	2×10^4	30	Lin and Ho [153]
P ITO PEDOT:PSS PEO-PC-LiClO ₄ PANI:CSA ITO P	4	T_{630} 0.64–0.22	15×10^3	30	Huang et al. [60]
P ITO PEDOT:PSS PEO-PC-LiClO ₄ PANI:PSS ITO P	4	T_{630} 0.65–0.25	–	–	–
P ITO PEDOT:DMF IL-BF ₄ ⁻ PEDOT:DMF ITO P	4	ΔT_{vis} 0.51	–	3/4	Pozo-Gonzalo et al. [115]
P ITO PEDOT:CVD salt electrolyte ITO PET	1	ΔT_{566} 0.48	150	13/8.5	Lock et al. [91]
P PANI Au PES PVOH PET Au P	–	$\Delta R_{800-1200}$ 0.24	–	–	Li et al. [89]

Table 3

Data for photovoltaic integrated electrochromic devices found in literature showing materials, sample size, modulation range, the performed number of cycles and the switching time for colouration and bleaching $\tau_{c/b}$.

Photovoltaic EC construction	Size (cm ²)	T (–)	Cycles	$\tau_{c/b}$ (s)	Reference
G ITO WO ₃ TiO ₂ IC TCO	–	T_{788} 0.70–0.54	–	120	Bechinger and Gregg [16]
G TCO WO ₃ :Li LiAlF ₄ V ₂ O ₅ TCO a-SiC:N–p–i–n TCO G	–	–	–	–	Deb et al. [25]
G WO ₃ :Li LiAlF ₄ V ₂ O ₅ a-SiC:H–p–i–n TCO G	–	T_{670} 0.60–0.10	–	–	Deb et al. [25]
G TCO WO ₃ TiO ₂ LiI:I ₂ :PC Pt TCO G	25	T_{sol} 0.26–0.02	–	120	Hauch et al. [56]
G ITO TiO ₂ – _x N _x NiO NaHCO ₃ /NaOH Pt	6	T_{500} 0.87–0.15	–	1 h	Huang et al. [61]

Table 4

Data for gasochromic devices found in literature showing materials, sample size, modulation range for the transmittance or reflectance, the performed number of cycles and the switching time for colouration and bleaching.

Gasochromic device construction	Size (cm ²)	T (–)	Cycles	$\tau_{c/b}$ (s)	Reference
G WO ₃ Pt H ₂ /Ar G	6600	T_{vis} 0.77–0.06 T_{sol} 0.76–0.05	20,000	20	Wittwer et al. [140]
G H ₂ /Ar Pd ITO Pd ZrO ₂ Pd Zr/ZrO ₂ MnNiMg ITO G	–	R_{sol} 0.80–0.15	1 000	–	Bao et al. [12,13]
G/P Pd:W-PTA Pt H ₂	–	T_{vis} 0.74–0.09	–	50/120	Orel et al. [105]
G/P Pd:W-PTA ICS-PPG Pt H ₂	–	T_{vis} 0.86–0.05	–	~200	
G/P Pt:WO ₃ Pt H ₂	–	T_{vis} 0.64–0.09	–	500/1000	

large-area applications are the possible loss of the energy generated by the PV device for larger dimensions, a small range of optical modulation and rather low transmittances in the clear state.

A wide band gap a-Si_{1–x}C_x:H n–i–p photovoltaic cell is employed [25,26,34,35] as a semitransparent power supply. The PV cell has a transmittance of 0.80 over most of the visible light and maintains a 1-sun¹ open-circuit voltage V_{oc} of 0.92 V and short-circuit current J_{sc} of 2 mA/cm² for a thickness of 60 nm. Whereas a transparent conductor, i.e. SnO₂, separated the PV and the electrochromic device (ECD) in the side-by-side solution, the low-voltage ECD is deposited directly on top of the PC device in the monolithic solution, and consists of lithium based tungsten oxide and vanadium oxide as counter electrode, i.e. Li_yWO₃–LiAlF₄/V₂O₅. By properly controlling the thickness of each layer the colouring and bleaching voltages have been adjusted for compatibility with the PV device. Colouration occurred within the range of –0.6 to –1.3 V and bleaching within 0.1–0.6 V, with colouring and bleaching times of approximately 2 min. The absence of a middle conductor in the monolithic PV–ECD requires that both the colouring and bleaching current flows through the PV and EC device all the time. Therefore, the 2 V bleaching voltage includes the part required to overcome the built-in potential from the PV of approximately 0.8 V. The ECD itself has a transmittance of 0.63–0.20 at 670 nm at –1.0 and +1.0 V, but much lower values T_{sol} of 0.25–0.08 are obtained for the complete PV–EC device.

The use of a dye–TiO₂ photovoltaic cell [16,56,113] resulted in the same low value T_{sol} of 0.26–0.02 [51] for a simple Li_yWO₃|dye–TiO₂ device. The PV device has a V_{oc} of 0.88 V, making it possible

to bleach and colour the EC device in about 2 min. Compared with this low transmittance, much better transmittances T_{500} of 0.87–0.15 have been obtained by combining a TiO₂–_xN_x with nickel oxide as electrochromic layer [61].

3.4.4. All-solid-state switchable mirrors

Recently, all-solid-state switchable mirrors have been achieved at the *National Institute of Advanced Industrial Science and Technology AIST* (Japan) based on both the switchable properties of Mg₄Ni and the electrochromic properties of H_xWO₃ [14,133]. Similar gasochromic switchable mirrors have been developed, as stated later-on in Ch.3.5, based on both MgNi_x and MnNiMg.

The device is a multilayer Mg₄Ni|Pd|Al|Ta₂O₅|H_xWO₃|ITO on a PET sheet. For the switching property, the protons in H_xWO₃ are transported to the layer of Mg₄Ni by applying voltage whereafter both layers will turn to their transparent state, while Mg₄Ni is highly reflecting in the metallic state. The resulting T_{vis} are 0.47–0.01 and switching occurred within 10–30 s when a voltage of 5 V was applied, depending on the ITO sheet resistance.

3.5. Gasochromic devices

The principle behind gasochromic windows is similar to that of solid-state gasochromic windows. An electrochromic is switched between a bleached and coloured state by hydrogen gas H₂ instead of applying a voltage. However, not all electrochromic materials can be coloured with hydrogen gas. The gasochromic devices are claimed to be simple and inexpensive, because only a single electrochromic layer is sufficient, and transparent electrically conducting layers are no longer necessary. The transmittance modulation of the gasochromic devices exceed these of most solid-state EC windows (see Table 4).

Gasochromic switching is an option for window applications, but it requires well controlled gas exchange processes. The effect has been studied in devices based on NiO, MoO₃ [102,144] and V₂O₅ [123], but the best results for smart windows have been obtained for tungsten-based gasochromic devices. Usually, a thin

¹ Light intensity I_{light} is generally expressed in *suns*, where 1 sun is 1 kW/m². As a result, the 1-sun open-circuit voltage V_{oc} represents the maximum voltage (at zero current) from a solar cell for a light irradiance of 1 sun or 1 kW/m² [71]. Here, the mentioned V_{oc} of 0.9 V is rather high. Silicon solar cells on high quality single crystalline material have a 1-sun V_{oc} up to 730 mV, while commercial devices typically have a 1-sun V_{oc} around 600 mV.

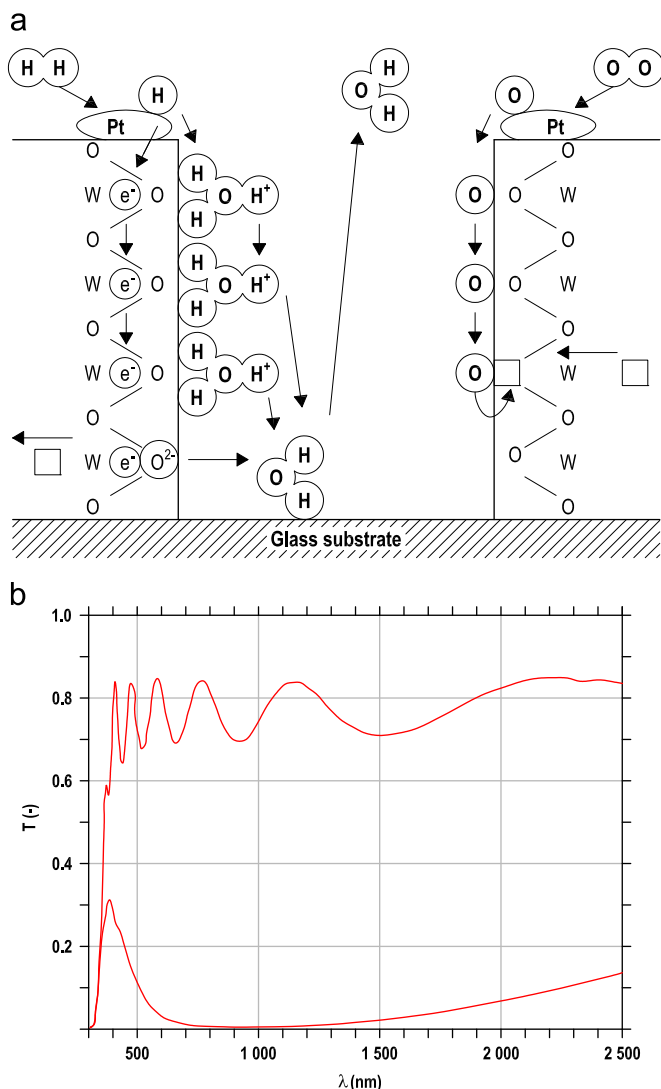


Fig. 7. [upper] Mechanism of colouration by H₂ in porous columnar WO₃. Dissociation of H₂ into 2H occurs on the upper surface catalysed by Pt, whereas the reaction leading to formation of colour centres occurs on the internal pore surfaces, after diffusions by the protons along the pores in the presence of water and mechanism of bleaching by O₂ (redrawn from [139]). [bottom] Transmittance for the coloured and bleached state of a gasochromic double-glazed unit with a WO₃ layer of 500 nm and a hydrogen concentration of 1% (redrawn from [139]).

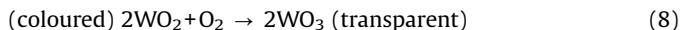
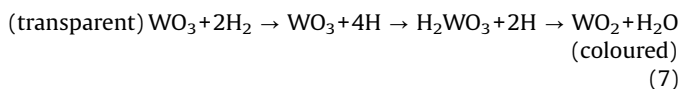
catalytic layer of Pt or Pd is incorporated to facilitate the gasochromic effect, but the oxides remain electrically non-conducting.

3.5.1. WO₃-based gasochromic windows

Gasochromic windows have been introduced based on the chromic properties of WO₃ [39–45,103,104,121,139,140,143] and palladium doped WO₃ [105,107,148] as stated previously in Ch.3.1. Due to its high redox potential, it is possible to colour WO₃ with hydrogen gas H₂ which is not possible for most other electrochromic materials.

The optically active material is a sputtered, highly porous, columnar film of (doped) WO₃ with a typical thickness around 400 nm, coated by a 1–5 nm thin catalytic layer of platinum Pt. Exposed to a low concentration of H₂ in a carrier gas, it colours blue. A more neutral colour, i.e. grey–blue, can be obtained by using a mixture of WO₃ with molybdenum oxide W_xMo_yO₃, but this will result in inferior transmittances. On exposure to O₂, the layer bleaches back to its original state (see Fig. 7). The exact

mechanism of gasochromic colouration is not completely yet known, but could be summarized as follows [103]:



Both the optical density and the rate of coloration can be varied by the choice of film thickness and/or gas concentration, but the dependence is weak. For testing, the gases were supplied from pressurized bottles, but generation of the gases by electrolysis is an obvious option and can be integrated into a façade without affecting the rest of the building.

Units with an area of 0.6 × 1.1 m² have been produced and tested over 20,000 cycles during three years without suffering any obvious damage. Transmittances T_{sol} of 0.76–0.05 and T_{vis} of 0.77–0.06 have been achieved. The transmittance is reduced to 10% of its original value within 20 s during the colouring process and is returned to 95% of this value within a minute by admitting 5% oxygen to the system. Colouring could be accelerated by increasing the film thickness and/or gas concentration.

3.5.2. Gasochromic switchable mirrors

A new possibility besides WO₃-based gasochromic windows has been brought up recently, resulting in the so-called gasochromic mirrors. These devices are based on the same principle: A MgNi_x alloy [12,15,139,145], MgTi [13] or MnNiMg [3,125] with a palladium Pd catalyst will turn transparent by taking up hydrogen. Similar all-solid-state switchable mirrors have been developed recently [14,133] as stated earlier in Ch.3.4.4 based on both Mg₄Ni and H_xWO₃.

The gasochromic device developed by Anders et al. [3] uses the cavity between both glass panes for the hydrogen storage (i.e. 0.01/0.99 H₂/Ar) and for which, as a result, gas transport is no longer necessary. In order to facilitate ion transport to and from the MnNiMg layer, a ZrO₂ ionic conductor and an ITO-layer are added as counter electrodes. The final device is H₂/Ar|Pd|ITO|Pd|ZrO₂|Pd|Zr|ZrO₂|MnNiMg|ITO for which the second Zr/ZrO₂ layer has been added to minimize diffusion of Pd into the MnNiMg layer

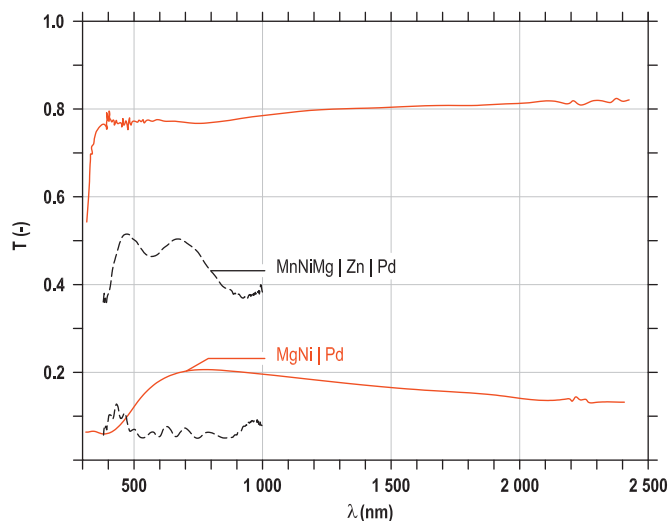


Fig. 8. Typical reflectance spectra of a MgNi_{0.15}|Pd and a MnNiMg|Zn|Pd gasochromic device (redrawn from [139] and [3]).

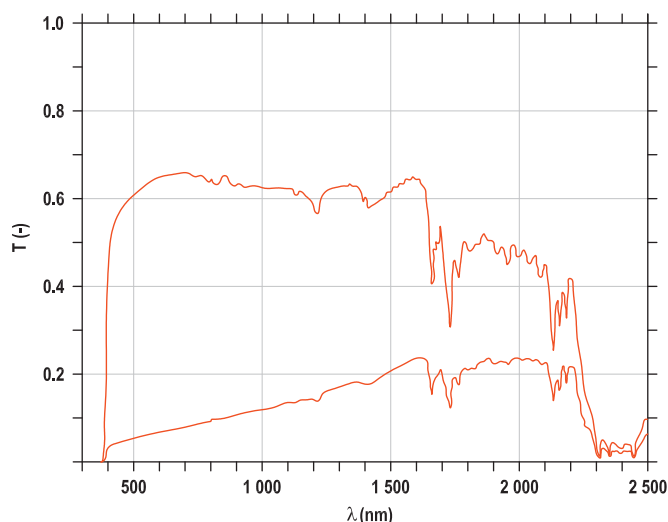


Fig. 9. Normal-normal transmittance spectra of polymer-dispersed liquid crystal laminated glass for an applied voltage of 50 VAC at 60 Hz in the ON state (redrawn from [108]).

and to protect the layer from oxidation. Films with a Mg content between 80% and 95% perform well (see Fig. 8), while an increased switching speed and a decreased upper end of the transmittance range is noticed with decreasing Mg content.

The stability of these devices still needs to be improved, i.e. typical degradation includes slowing down of the kinetics, related to Pd catalyst mobility. Degradation occurs quickly after 100–150 cycles [3], but up to 1000 cycles have been achieved [12,13] by coating the metal layer with polyvinylacetate PVAc and cellulose acetate CA. Simultaneously, the transmittance in the non-metallic state increased with ~ 0.1 for wavelengths above 750 nm by coating with PVAc.

4. Liquid crystal devices

Switchable devices based on liquid crystals (LC) offer another approach besides electrochromic and gasochromic devices. The mechanism of optical switching is a change in the orientation of liquid crystal molecules between two conductive electrodes by applying an electric field, resulting in a change of their transmittance [28,32]. Liquid crystals come in six different types, i.e. nematic, smectic, twisted nematic, cholesteric (ChLCs), guest-host and ferroelectric, but mainly guest-host liquid crystals are applied in commercial switchable windows since the 1990s, of which polymer-dispersed liquid crystals (PDLC) and encapsulated liquid crystals (NCAP) are the most common [77–79]. Large-area PDLC windows are already commercially available, i.e. in sizes up to $1.0 \times 2.8 \text{ m}^2$ by Saint-Gobain glass, and operate between 24 and 120 V. Recent research on commercial products show good results: A $20 \mu\text{m}$ commercial PDLC layer by DM Display Co. Ltd. (Korea) has been used between ITO coated polyester films to achieve a $20 \times 20 \text{ cm}^2$ device with T_{uv} 0.018–0.001, T_{vis} 0.62–0.061 and T_{nir} 0.384–0.129 (see Fig. 9), while the haze coefficient changes from 0.09 to 0.90 [108]. The device exhibits good temperature stability between 0 and 60°C , while a device of $125 \times 350 \text{ cm}^2$ has been developed and found to be stable for 3 million times switching at 100 VAC.

However, the devices require continuous power resulting in a power consumption of 5 up to 20 W/m^2 , while also long-term UV stability and high cost remain issues.

Comparable values for the transmittance have been achieved [37] for organosiloxane liquid crystals, but more remarkable is T 0.80–0.01 at λ_{max} (unknown) achieved [22] by using the liquid crystalline monomer 1,4-bis{4-[6-(acryloyloxy)hexyloxy]-benzoyloxy} benzene, which is known for its possibility to allow and keep a good homeotropic alignment of liquid crystals on ITO-covered substrates after polymerization. The values are achieved after colouring and bleaching times of, respectively, 2 and 0.5 min.

Similar to the EC devices, one has developed a liquid crystal device including an a-Si_{1-x}C_x:H n-i-p photovoltaic cell, but the device turns out to be relatively dark with transmittances below 0.31 [24].

5. Electrophoretic or suspended-particle devices (SPD)

SP devices are similar to LC devices in different ways: Both technologies were initially developed for displays meaning that they are relatively fast compared with other technologies and both rely on the electronic field to align the active elements to let light though undisturbed.

Electrophoretic of suspended particle (SP) windows is a film-based patented technology developed and licensed by Research Frontiers Inc. (NY, USA) and their licensees [19]. SPDs consist of 3–5 layers of which the active layer has adsorbing dipole needle-shaped or spherical particles, i.e. mostly polyhalide, suspended in an organic fluid or gel between two transparent conductors. The particles are random and light absorbing in the off state, but will align by application of an electric field causing an increase in transmittance. SPD devices have typical transmission ranges of 0.79–0.49 and 0.50–0.04, a switching time of 100–200 ms and require 65–220 V AC to operate.

Due to the patents on the technology, only little information has been found on recent developments of suspended particle devices [137].

6. Commercially available smart windows

The technology of electrochromism, liquid crystal switching and electrophoretic switching was discovered and made publicly in the 1970s and the 1980s, but the progress has been slow. The glass industry has been trying for some decades, but up to recently no smart windows made it to the market. However, the market of smart windows is changing due to extensive energy regulations for buildings and the need for *alternative* solutions. In the last decades, many glass and coating manufacturers brought *smart glass* on the market for building and automotive purposes, based on EC, LC and SPD technologies. In order to control daylight and solar energy in buildings, it is important to know how current commercially available smart windows perform, which properties they exhibit and how reliable the products are. Answering these questions is the main aim in this work.

Before discussing the available products on the market today, it is important to look for which properties are actually desired for daylight and solar energy control in buildings.

6.1. Requirements and expectations

The required properties for smart windows for solar and energy applications have been expressed by Lampert [76] (see Table 5) and surveys have recently been performed [128–132] of

Table 5
Requirements for electrochromic windows in the bleached (bl.) and coloured (col.) state [76].

Solar transmission (–)						Solar reflection (–)		Switching voltage (V)		Memory (h)	Cycling lifetime	Operating temperature
T_{sol}		T_{vis}		T_{nir}		R_{nir}						
bl.	col.	bl.	col.	bl.	col.	bl.	col.	Small	Large	1–12	> 10 ⁴ –10 ⁶ cycles 5–20 years	Unprotected
0.50–0.70	0.10–0.20	0.50–0.70	≤ 0.10–0.20	–	–	0.10–0.20	≥ 0.70	1–3	10–24			– 30–70 °C

United States architects, LEED² accredited professionals and window manufacturers on the subject of switchable windows by *Research Frontiers Inc.*

The attitudes towards smart glass are strongly positive. Leading drivers are the potential for greater energy savings, a demand for sustainable building solutions and the need for lower lifetime operating costs of buildings, while also aesthetics, e.g. view preservation and furnishing protection, become more and more important. In general, energy efficient operation and high durability are desired, while operation using alternating current voltage is preferred above direct current voltage. Regarding the performance of the smart windows, the most desired properties are (i) integration with other coatings, e.g. low-e, (ii) glare reduction, (iii) consistent-looking tint changes regardless of window size, (iv) light control to any point between the dark and clear transparent state, (v) a high blockage of UV light, and (vi) fast switching speeds. It is the professionals opinion that a maximum size of $3 \times 2 \text{ m}^2$ is desired and a median of 500 \$/m² is expressed as a maximal cost for both commercial and residential projects.

Although the awareness of smart windows is moderately strong on the commercial market, the knowledge of specific characteristics of switchable glass has been found limited. Lack of knowledge regarding the product category, uncertainties about the actual service life of smart windows and the perception that the material costs associated with switchable windows are excessively high have been found to be the primary inhibiting factors why architects have not yet applied smart windows. However, the outlook for smart windows is strong. It was projected [33] that the dollar value of the smart window demand in the United States will reach \$ 1.34×10^9 by 2015, i.e. a 250% increase compared with 2005.

6.2. Transparent conductors

The most-used transparent conductor ITO is widely commercially available, but also the poly(3,4-ethylene-dioxythiophene) PEDOT and carbon nanotube CNT alternatives (see Ch.2) are yet limited available on the market.

Both *Asahi glass* (Yokohama, Japan) and *präzisions glas & optik* (Germany) have shown the capability to produce a large-area ITO glass of 1 m² with a sheet resistance of $1 \Omega/\square$ or lower and low haze. On the other hand, *Diamond Coatings* (United Kingdom) has shown the ability to produce commercial highly transparent ITO-coatings with transmittances up to 0.95 in the visible spectrum for a sheet resistance of 10–20 Ω/\square .

Transparent conductive PEDOT or PEDOT-based polymers have been recently introduced on the market by *H.C. Starck* (Germany)

and *Agfa-Gevaert* (Belgium). The coatings have a transmittance around 0.80, but still a relatively high sheet resistance of 150–500 Ω/\square . Also CNTs are yet commercially available, but only *Unidym* (CA, USA) expresses the possibility as large-area transparent conductive layer for large-area energy and solar applications. However, no properties on transmittances and conductivities are expressed.

Because PEDOT and CNTs are already limited available on the market and their high potential for future applications, they seem the best basis for new sustainable smart windows. However, as long as their long-term stability have not yet been proven, commercially available smart windows keep on using the standard transparent conducting oxides as ITO and FTO. Additional information about various manufacturers of transparent conductors is found in Appendix A.

6.3. All-solid-state electrochromic windows

Although many manufacturers claim to have ‘electrochromic smart windows’, only three companies, i.e. *SAGE Electrochromics*, *EControl-Glas* and *Gesimat* [31,46,117] have been found by the authors of this state-of-the-art review producing windows for possible exterior building glazing, which are truly based on electrochromics. An overview is given on the properties of EC windows on the market today and conclusions on the applicability of the commercial windows for daylight and solar energy control are stated. Besides these three companies which will be treated extensively, other smaller ones have to be mentioned: Also *Saint Gobain Sekurit* (France), *ChromoGenics* (Sweden) and *Gentex* (MI, USA) [20,38,118] produce electrochromic glass on small scale, mainly for automotive applications, but nothing or little is known on their properties. Further information about various manufacturers of commercially available electrochromic windows and devices is found in Appendix B.

6.3.1. Properties of available all-solid-state electrochromic windows

The first company that provides EC windows on the market today is *SAGE Electrochromics* (NY, USA) [117] which uses absorptive tungsten oxide as the electrochromic material. *SAGE* has been recognized worldwide for its electrochromic technology and has been referred to by many in the American construction community as ‘the only one’ suitable for the building window industry. So far, the company has the first and only commercially available electrochromic windows for exterior applications which passed ASTM E-2141-06, the standard American test methods for assessing the durability of absorptive electrochromic coatings on sealed insulating glass units.

The second company is *EControl-Glas* (Germany) [31]. This company has taken over the electrochromic activities of *Pilkington AG* (Suisse) and provides electrochromic glass for exterior building applications according to EN ISO 12543-4, the European standard

² LEED denotes Leadership in Energy and Environmental Design, where LEED Accredited Professionals indicates that they have passed the accreditation exam given by the Green Building Certification Institute of the United States Green Building Council (USGBC).

Table 6

Data for commercially available electrochromic windows for building applications found, showing maximum size, modulation range, the guaranteed number of colouring/bleaching cycles, the solar factor SF and the U -value of the entire window in $\text{W/m}^2\text{K}$ [31,46,117].

Manufacturer	Size (cm^2)	U	$T_{\text{sol}} (-)$	$T_{\text{vis}} (-)$	SF	Cycles
SAGE Electrochromics, Inc. (WO_3)	108×150	1.65	0.40–0.015	0.62–0.035	0.48–0.09	10^5
EControl-Glas GmbH and Co. KG (WO_3)	120×220	1.1	0.50–0.15	–	0.36–0.12	10-year guarantee
		0.5	0.45–0.14	–	0.30–0.10	–
Gesimat GmbH (WO_3 and CE)	80×120	–	0.52–0.06	0.75–0.08	–	10-year guarantee

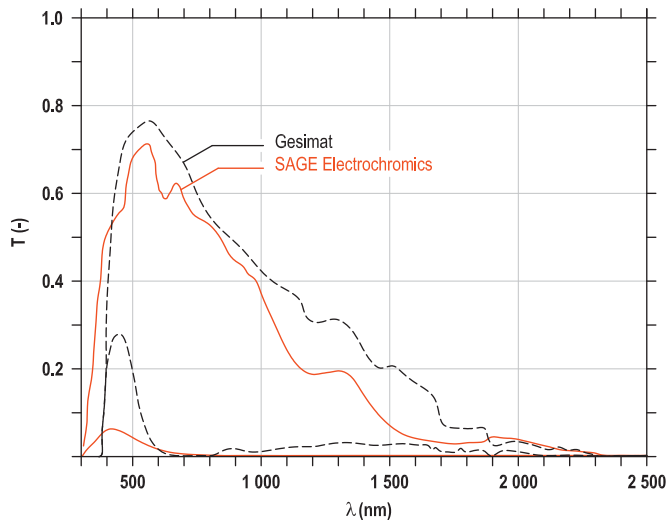


Fig. 10. Transmittance spectra of commercial products of Gesimat and of SAGE Electrochromics (redrawn from [46,119]).

test methods for the durability of laminated glass for building applications. According to literature, both manufacturers use a single WO_3 -layer for the electrochromic properties of their windows.

A third manufacturer of EC glass has been found in Gesimat (Germany) [46], which assembles EC windows conforming a slightly different process. A first difference may be found in the ion-conducting layer: An ion-conductive polyvinylbutyral (PVB) sheet is used, which is commonly used as a layer in safety glass and easily processed within the industry. A second difference may be found in its electrochromic layers. Where the previously mentioned manufacturers use a single tungsten oxide layer for its electrochromic properties, Gesimat applies two complementary layers, i.e. WO_3 and an unknown anodic EC. However, no information is found on the applicability of their products for building envelopes and their maximum sizes are smaller.

Properties of these commercially available windows are given in Table 6.

We may now compare the properties of the commercially available EC windows (Table 6) with the previously stated requirements or desired properties (Table 5):

- i. Both SAGE and EControl-Glas show the capability of producing large-area windows of, respectively, 1.6 and 2.6 m^2 , but can not reach the previously expressed desired dimension of $2 \times 3 \text{ m}^2$.
- ii. All EC windows operate at 5 V DC and have a low power consumption of 0.5 Wh/m^2 or lower, making them suitable

for working in symbiosis with photovoltaic devices, but more difficult to integrate in the electric network of a building.

- iii. A lifetime of 10^5 cycles and 30 years has been expressed within the range of -30 to 60°C by SAGE, which conforms the desired properties by Lampert [76]. No durability properties are found for the two other manufacturers, but both SAGE and EControl-Glas serve a 10-year guarantee on their windows.
- iv. Eight different types of electrochromic windows from SAGE, EControl-glas and Gesimat are so far found to be available on the market, of which a summary of the best windows is expressed in Table 6. Compared with the desired properties as expressed in Table 5, a few conclusions can be made. Firstly, the transmittance in the visible spectrum for the best performing windows of SAGE and Gesimat are satisfying the requirements (see Fig. 10), while the other products (of SAGE and Gesimat) are rather dark with a transmittance between 0.48 and 0.35 in the bleached state. No T_{vis} values are found for EControl-Glas. Secondly, the same can be said about the transmittance in the complete solar spectrum: The transmittance for the coloured state are low enough with values between 0.15 and 0.01, but the transmittance for the bleached state does not exceed 0.52 for all available windows. A possible reason here is the incorporation of a low-e coating. In overall, the electrochromic properties of the standard available windows of both SAGE and EControl-glas seem comparable: All have a range ΔT_{sol} between 0.35 and 0.40 which is far from the best-performing EC windows found in literature with a ΔT_{sol} of 0.68 and a ΔT_{vis} of 0.74, while the electrochromic properties of the Gesimat product has higher modulation ranges due to its two active EC layers.
- v. EControl-Glas achieves low U -values of 1.1 and $0.5 \text{ W/m}^2\text{K}$ by using an argon-filled cavity or triple glazing. On the other hand, SAGE only provides windows with a thermal U -value of $1.65 \text{ W/m}^2\text{K}$, whereas a value of $1.1 \text{ W/m}^2\text{K}$ has become standard in new European building projects.

To determine which manufacturer provides the best electrochromic windows is not possible because this strongly depends on the goals stated for implementing electrochromic windows in the actual building. SAGE Electrochromics is widely known for its electrochromic windows, while EControl-Glas has shown the capability of combining the EC properties with low U -values and manufacturing larger windows and Gesimat has shown the competence of manufacturing highly contrasting windows. Improvements on scale and higher transmittances for the commercial windows in the bleached state are desired, but the overall conclusion may be clear: One has shown the possibility to produce large-area electrochromic windows according to the standards for exterior building glazing with a good durability and EC properties.

Table 7

Data for commercially available LC-based smart windows for building applications found, showing maximum size, modulation range, the guaranteed number of colouring/bleaching cycles, the solar factor SF and the U -value of the entire window in $W/m^2 K$ [29,62,99,122,126].

Manufacturer	Size (cm^2)	U	T_{sol} (–)	T_{vis} (–)	SF	Cycles
Typical values, e.g. <i>SmartGlass</i> , <i>DreamGlass</i> and <i>SGG</i> .	100×280	–	ΔT 0.02	ΔT 0.02	–	10^6
Nippon Sheet Glass Co., Ltd.	180×275	–	–	0.69–0.12	–	–
Innovative Glass Corporation	260×488	1.6	–	0.77–0.56	–	–

Table 8

Data for commercially available SP-based smart windows for building applications found, showing maximum size, modulation range, the guaranteed number of colouring/bleaching cycles, the solar factor SF and the U -value of the entire window in $W/m^2 K$ [2,62,114,126].

Manufacturer	Size (cm^2)	U	T_{sol} (–)	T_{vis} (–)	SF	Cycles
Typical values, e.g. <i>SmartGlass</i> , <i>American glass products</i> , <i>pleotint</i> and <i>innovative glass corporation</i> .	100×280	–	0.50–0.04	0.35–0.18	0.50–0.30	10^6
American glass products company	$110 \times (-)$	–	–	0.79–0.49	–	10^5

6.3.2. Aesthetic and energetic consequences of available all-solid-state electrochromic windows

A field study has been performed on large-area commercial electrochromic windows of *SAGE* (Table 6) by the *Lawrence Berkeley National Laboratory* (CA, USA) [81–88]; Carmody et al. [154] Clear et al. [155]) of which the final results have been published by Lee et al. [86]. These field tests, together with simulations, allowed the quantification of the EC window performances for realistic office conditions. The conclusions of the field study can be recapitulated as follows:

- Switching from fully coloured to fully bleached takes 6–7 min at temperatures above $10^\circ C$ for windows of $0.46 \times 0.89 m^2$, while switching times between 40 and 85 min have been noted at colder temperatures and at low solar irradiance. These values are high, especially for low temperatures, and faster switching speeds are desired. Also, the switching range decreased over the 2.5-year installed period.
- Controlling the commercial EC window wall to maximize daylight and energy efficiency resulted in a *high* average daily lighting energy saving of 44% compared with a reference case with fully lowered blinds and without daylight-controlled electric lighting. However, the values are much lower, i.e. 26% and 10% if well-tuned daylighting control is applied as reference case and if the EC window is controlled to meet visual comfort, respectively. Controlling the commercial EC window wall for glare *hardly* reduced the average daily cooling loads due to solar heat gains, i.e. 8% and 3%, respectively, for a reference window without and with fully lowered blinds. Even more, using a split-façade EC window raised the average cooling loads due to solar heat gains by 11% compared with a shaded reference case.
- The EC system provides potentially large savings in electric demand for perimeter zones on warm days in hot climates: the windows *strongly* reduced peak cooling loads, i.e. by 26% and 19%, respectively, for a reference window without and with fully lowered blinds. However, much lower impacts will be noticed in cooler climates, in built-up urban areas (casting shadows) or for small windows.

According to the above studies, achieving maximum energy reduction via electrochromic windows requires controlling the

window and lighting systems in order to minimize lighting energy rather than to reduce solar heat gains, primarily because the coefficient of performance of conventional heating, ventilating and air conditioning (HVAC) systems shows little daily variation. However, the estimated energy impacts are highly dependent on the assumed reference case and the actual EC window performance properties, and more long-term studies are needed on the human behaviour factor.

6.4. Gasochromic windows

The transmittance modulation of prototype gasochromic windows exceeds these of most all-solid-state electrochromic windows. A pilot production plant for windows up to $1.5 \times 2.0 m^2$ has been built by *The Fraunhofer Institute for Solar Energy Systems and Interpane* (Germany) where transmittances T_{sol} of 0.76–0.05 and T_{vis} of 0.77–0.06 have been achieved, but no commercially available gasochromic windows have been found.

6.5. Liquid crystal smart windows

Liquid crystal devices are commercial widely available for large-area applications. An overview is given in Appendix B on the most-known manufacturers of LC windows (see also Table 7), but many more manufacturers are on the market today.

Commercial LC windows have been found stable for temperatures between 0 and $60^\circ C$ and large-area windows of up to $12 m^2$ are on the market, but long-term UV stability remains an issue. However, the resulting modulation ranges seem less favourable for energy-related applications in building envelopes. Average modulation ranges are 0.02 for both ΔT_{vis} and ΔT_{sol} . The main modulation by switching LC windows is obtained in hazing the light transmission. The haze coefficient switches from about 0.90 to 0.08, but the haze coefficient stays relatively high in the transparent mode (i.e. less clear). Two manufacturers, i.e. *Nippon Sheet Glass Corporation* (Japan) and *Innovative Glass Corporation* (NY, USA), have higher modulation ranges ΔT_{vis} of 0.57 and 0.21, respectively.

All available LC windows operate between 65 and 230 V AC, but constant power is necessary in the clear state resulting in a power consumption of 3.5 up to 15.5 W/m² in contrast to electrochromic windows where power only is necessary during switching.

As a result of this, liquid crystal devices are commonly only applied in buildings for aesthetic or privacy applications instead of solar energy control.

6.6. Suspended-particle smart windows

The market on suspended-particle (SP) based windows is patented technology and completely licensed by *Research Frontiers Inc.* (NY, USA) and their licensees. An overview is given on the properties of SP windows on the market today and conclusions on the applicability of the commercial windows for daylight and solar energy control are stated. Additional information about various manufacturers of commercially available suspended particle-based smart windows and devices is found in Appendix B.

6.6.1. Properties of available SP windows

Many commercial SP windows are available today from different manufacturers with sizes up to 2.6×4.9 m², but all have a similar transmittance modulation with a T_{vis} of 0.50–0.04 and stability for more than 10^6 cycles between -20 and 65 °C (see e.g. Table 8). Darker windows are available, but it is questioned whether this is favourable with the already low maximum transmittance of 0.50. Similar to LC windows, all available SP windows operate between 65 and 220 V AC, where a constant power is necessary to maintain the clear state, resulting in a power consumption of 1.9 up to 16 W/m² in contrast to electrochromic windows where power only is necessary during switching.

One exception to the relatively dark windows may be noticed: *American Glass Products Company* (TN, USA) [2] provides windows with a T_{vis} of 0.79–0.49, but the company mainly provides automotive glazing and no exterior building glazing products have been found.

6.6.2. Applicability of available SP windows

A commercial 0.28×0.22 m² suspended-particle window of *Cricursa Cristales Curvados* (Spain) [21] has been tested on the applicability as smart window for building purposes [137]. Here, the response times have been found much shorter, i.e. between 2 and 3 s, compared with the longer switching times in EC windows. However, two major concerns are expressed regarding possible wide-spread building applications:

- i. The device could only be cycled for less than 1000 switches before breakdown, due to stresses caused by abrupt changes in the applied voltage, which is significantly poorer than expected by the information given by the company.
- ii. The optical direct transmittance in the clear state is poor, i.e. below 0.25.

Conclusion of the study stated that future research should focus on new materials and manufacturing processes to improve cyclability and obtain better transmittance ranges.

7. Conclusions

Electrochromic and electrophoretic or suspended-particle windows seem highly promising for dynamic daylight and solar energy applications in buildings based on the achieved transmittance modulation ranges. The transmittances in the solar spectrum, the guaranteed number of cycles and the maximum window sizes are similar for the commercial products of both technologies. The maximum transmittance as well as the modulation range in the visible spectrum is *much* higher for electrochromic windows, though. On the other hand, the transmittance modulation has been found poor for commercial liquid crystal windows. In addition, the liquid crystal windows have been found instable for UV radiation and as a result inappropriate for long-term exterior building applications. Liquid crystal and suspended-particle windows share the same disadvantages: Both need an electric field to be maintained as long as the transparent mode of the glass is required, resulting in a higher energy consumption compared with electrochromic windows which normally only require an electric field during switching.

Currently, based on this literature survey, electrochromic windows seem to be the most promising state-of-the-art technology for daylight and solar energy purposes. The reliability of the current commercially available windows has been proven, their properties are within expectations and room for improvements has been demonstrated in literature. The windows have been found to be able to reduce up to 26% of lighting energy compared with well-tuned daylighting control by blinds, and around 20% of the peak cooling loads in hot climates as California (USA). However, little is known about their efficiency in colder, e.g. Nordic, climates.

Gasochromic windows are recently being developed and show promising results. Due to its simple device structure and the absence of transparent conductors, very high transmittance modulation ranges compared with the short research period have been achieved. This may also mean that future commercial gasochromic windows may become an economically attractive high performance alternative for current smart window technologies. However, negative aspects such as the use of gas and a limited available number of cycles must be mentioned.

Acknowledgements

This work was supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackon, maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodu-sentenenes forskningsgruppe through the SINTEF/NTNU research project 'Robust Envelope Construction Details for Buildings of the 21st Century' (ROBUST).

Appendix A. List of transparent conductor manufacturers

See Table A1.

Appendix B. List of smart window manufacturers

See Table A2.

Table A1





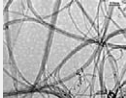

Manufacturer	Illustration	Product	T_{vis}	T_{sol}	T_{uv}	Sheet resistance	Size	Further Information
Transparent conducting ITO								
präzisions glas & optik, Gmbh, Im Langen Busch 14, D-58640 Iserlohn, GERMANY Tel.: +49 2371 77679 0; fax: +49 2371 77679 70 info@pgo-online.com, www.pgo-online.com		CEC-series	–	~0.70	–	< 5 up to 10,000 Ω/\square	–	– ITO-coated glass
Diamonds Coatings Limited, Unit 2a, Harvey Works Ind. State, Shelah Road, Halesowen, UK Tel.: +44 845 1630603; fax: +44 845 1360604 www.diamondcoatings.co.uk		DIAMOX ITO	T_{max} 0.79–0.89	–	–	10–50 Ω/\square	100 × 100 cm ²	– ITO-coatings
		DIAMOX+ITO	T_{max} 0.93–0.85	–	–			
AGC Asahi Glass co.Ltd, Strawinskylaan 1525, 1077 Amsterdam, NETHERLANDS Tel.: +31 20 5736040; fax: +31 20 5753191 www.agc.co.jp		–	–	–	–	Down to 1 Ω/\square	–	– ITO-coated glass
Transparent conducting PEDOT								
H.C. Starck GmbH, Im Schleeke 78–91, 38642 Goslar, GERMANY Tel.: +49 53 21 7 51 0; fax: +49 53 21 7 51 61 92 www.clevios.com		Clevios™ P grades	> 0.80	–	–	Down to 150 Ω/\square	–	– PEDOT coating
Agfa-Gevaert, Septestraat 27, B-2640 Mortsel, BELGIUM Tel.: +32 3 444 2111; fax: +32 3 444 4485 Info.orgacon@agfa.com, www.agfa.com		Orgacon™	–	–	–	< 200 Ω/\square	–	– PEDOT coating
Transparent conducting carbon nanotubes								
NANOCS, 244 Fifth Avenue, #2949, 10001 NY, USA Tel.: +1 888 908 8803; fax: +1 917 591 2212 sales@nanocs.com, www.nanocs.com		ITO-series	> 0.85	–	–	8 up to 100 Ω/\square	–	– ITO
		CNT-series	–	–	–	–		– Carbon nanotubes CNT
		NCS-series	–	–	–	–		– Nano Gold Coating
Chengdu Organic Chemicals Co. Ltd. Tel.: +86 28 85236765 85228839; fax: +86 28 85215069 85223978 carbon@cioc.ac.cn, www.timesnano.com		SWCNT	–	–	–	EC > 100 S/cm	–	– Single-wall Carbon nanotubes NTC
Unidym, Inc., 1430 O'Brien Drive, Suite G, Menlo Park, CA 94025, USA Tel.: +1 650 462 1935; fax: +1 650 462 1939 www.unidym.com		HIPCO® Single- Wall Carbon Nanotube	–	–	–	–	'large-area'	– Carbon nanotubes CNT

Table A2











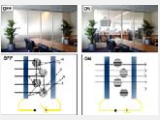


Manufacturer	Illustration	Product	U_{window} (W/m ² K)	T_{vis}	T_{sol}	T_{uv}	SF	Durability	Max size	Electrical demand	Further Information
Commercially available electrochromic windows and devices											
SAGE Electrochromics, Inc., One Sage Way, Faribault, MN 55021, USA Tel.: +1 877 724 3321; fax: +1 507 333 0145 sales@sage-ec.com, http://www.sage-ec.com/		Classic TM	1.65	0.62–0.035	0.40–0.015	0.056–0.008	0.48–0.09	100 000 cycles, 30 yrs, –30 to 60 °C	Up to 108 × 150 cm ²	5 VDC	Electrochromic windows for building applications Switching time of 3–5 min 10 years warranty Only commercially available smart windows for exterior applications which passed ASTM E-2141-06WO ₃ -based
		See Green TM	1.65	0.62–0.035	0.40–0.015	0.004–0.001	0.48–0.09				
		Cool View Blue TM	1.65	0.48–0.028	0.19–0.01	0.04–0.006	0.44–0.09				
		Clear-as-Day TM	1.65	0.40–0.023	0.30–0.01	0.000–0.000	0.46–0.09				
EControl-Glas GmbH & Co. KG, Glaserstr.1, 93437 Furth im Wald, GERMANY Tel.: +49 9973 858 330; fax: +49 9973 858 331 info@econtrol-glas.de, www.econtrol-glas.de		EControl [®] Double Glass	1.1	–	0.50–0.15	0.05–0.005	0.36–0.12	–	120 × 220 cm ²	5 VDC < 0.5 Wh/m ²	Electrochromic windows for building applications According to DIN EN ISO 12543-4 for exterior insulating glass-WO ₃ -based
		EControl [®] Triple Glass	0.5	–	0.45–0.14	0.02–0.003	0.30–0.10				
GESIMAT GmbH, Koepenicker Str. 325, 12555 Berlin, GERMANY Tel.: +49 30 473 89 251; fax: +49 473 89 252 www.gesimat.de		–	–	0.75–0.08	0.52–0.06	–	–	–	120 × 80 cm ²	0.5/2.2 V DC, 0.04 Wh/m ²	Electrochromic window based on EC and active counter-ECWO ₃ +active CE
ChromoGenics AB, Märstagatan 4, SE-75323, Uppsala, SWEDEN Tel.: +46 18 430 04 30 info@chromogenics.be, www.chromogenics.se	–	–	–	–	–	–	–	–	–	–	Electrochromic window based on WO and NiO
Saint Gobain Sekurit, Viktoriaallee 3-5, 52066 Aachen, GERMANY Tel.: +49 241 947 2604 contactSekurit@Saint-Gobain.com, www.sekurit.com		SGS Electrochromic Glass	–	0.40–0.04	0.20–0.02	–	–	–25–90 °C	–	1.5 V DC < 0.1 Wh/m ²	Electrochromic window for automotive applications
IP Glass Technology B.V., 159 Groenendaal, 3011 SR Rotterdam, NETHERLANDS Tel.: +31 10 213 67 52; fax: +31 10 213 17 09 info@intraprojects.com, www.intraprojects.com		SPD Glass	–	–	–	–	–	–	–	–	Electrochromic Glass in cooperation with SAGE Electrochromics
		ECD Glass	–	–	–	–	–	–	–	–	
		LCD Glass	–	–	–	–	–	–	–	–	
GENTEX Corporation, 600 North Centennial St., Zeeland, 49464 MI, USA Tel.: +1 616 772 1800; fax: +1 616 772 7348 www.gentex.com		Gentex Auto-Dimming	–	–	–	–	–	–	–	–	Electrochromic mirrors for automotive applications.
AJER LLC., 4541E Fort Lowell Road, Tucson, AZ 85715, USA Tel.: +1 520 321 7680x28; fax: +1 520 321 0030 aagrawal@gwestoffice.net, www.ajer.com		Electrochromix Inc	–	–	–	–	–	–	–	–	Electrochromic automotive mirrors & building glazing

Table A2 (continued)

Manufacturer	Illustration	Product	U_{window} (W/m ² K)	T_{vis}	T_{sol}	T_{uv}	SF	Durability	Max size	Electrical demand	Further Information
Commercially available liquid crystal-based smart windows and devices											
SmartGlass International, Ltd. , (See SPD-based smart windows) www.SmartGlassinternational.com		LC SmartGlass™	1.3	0.65–0.58	0.51–0.49	0.06–0.06	–	3×10^6 cycles, 12 yrs, –20 to 50 °C	Up to 98.6 × 290 cm ²	65–110 VAC, < 200 mA/m ² , 5 W/m ²	Polymer-dispersed liquid crystal device (PDLC). Diffuse light when switched on
DreamGlass , C/ Cañada, 15. 28860 Paracuellos del Jarama, Madrid, SPAIN Tel.: +34 91 658 42 45; fax: +34 91 658 14 51 www.dreamglass.es		DreamGlass V1®	–	–	0.75–0.71 (hazed)	–	–	–10–50 °C	120 × 300 cm ²	60–80 VAC, 10 W/m ²	Liquid crystal device (LC)
		DreamGlass V2®	–	–	0.79–0.75 (hazed)	–	–	0–65 °C	100 × 300 cm ²	100–120 VAC, 8 W/m ²	
Saint-Gobain Glass , Les Miroirs 18, avenue d'Alsace, 92400 Courbevoie, FRANCE Tel.: +33 1 47 62 30 00 glassinfo@saint-gobain-glass.com, www.sggprivalite.com		Priva-Lite 55.2 (11 mm)	5.6–5.8	0.77–0.76	–	–	0.63–0.64	–20–60 °C	100 × 280 cm ²	230 VAC, < 5 W/m ²	NCAP LC; Haze 0.075–0.90; Reflectance 0.19–0.18
		Priva-Lite 55.2 (28 mm)	1.3–2.6	0.69–0.68	–	–	0.59–0.59				NCAP LC; Haze 0.075–0.90; Reflectance 0.23–0.23
LTI Smart Glass Inc. , 175 Crystal Straat PO Box, 2305 Lenox, MA 01240, USA Tel.: +1 413 637 5001; fax: +1 413 637 5004 http://ltisg.com/3.0/switchable.php		–	–	–	–	–	–	–	–	110 VAC	Liquid crystal device (LC)-Bulletproof privacy glazing
Nippon Sheet Glass Co., Ltd. , 2-1-7 Kaigan, Minato-ku, Tokyo, 105-8552, JAPAN Tel.: +81 3 5443 9522 http://www.nsg.co.jp/en/		UMU™	–	0.69–0.12 Ref. [78]	–	UV instable	–	–20–60 °C	180 × 275 cm ²	100 VAC, 3.5 W/m ²	NCAP LC for automotive and building applications
Scienstry, Inc. , 1110E Collins Blvd.Ste120, Richardson, TX 75081, USA Tel.: +1 972 690 5880; fax: +1 972 690 5888 info@scienstry.us, www.scienstry.us		NPD-LCD	–	–	–	–	–	–	–	–	Liquid crystal glazing (LC) 0.145 up to 3.3 mm < 5 up to 10,000 Ω/□
Innovative Glass Corporation (see SPD-based smart windows) www.innovativeglasscorp.com		LC Glass™	1.6	0.77–0.56	–	0.01	–	–20–70 °C	260 × 488 cm ²	120 VAC, 130 mA/m ² , 15.5 W/m ²	Liquid crystal device (LC)
Commercially available suspended-particle-based smart windows and devices											
Research Frontiers Inc. , 240 Crossways Park Drive, Woodbury, 11797 NY, USA Tel.: +1 516 364 1902; fax: +1 516 364 3798 http://www.refr-spd.com		SPD Smart™	–	–	–	–	–	–40–100 °C	Max. width 150 cm		SPD for automotive and building applications
SmartGlass International, Ltd. , Unit 21, Cookstown Industrial Estate, Tallaght, Dublin 24, IRELAND Tel.: +353 1 4629945; fax: +353 1 4629951 info@smartglassinternational.com, www.SmartGlassinternational.com		SPD SmartGlass™	1.3	0.49–0.0024	–	0.005–0.005	–	3×10^6 cycles, 12 yrs, –20 to 50 °C	Up to 98.6 × 290 cm ²	65–110 VAC, < 200 mA/m ² , ~5 W/m ²	Suspended particle device (SPD)

Cricursa Cristales Curvados S.A., Cami de Can Ferran s/n, Pol. Industrial Coll de la Maya, 08403 Granollers (Barcelona), SPAIN Tel.: +34 93 840 4470; fax: +34 93 840 1460 cricursa@cricursa.com, www.cricursa.com	CRI-Regulite	A	1.29	0.17–0.004	0.23–0.11	-	0.35–0.21	> 1,000,000 cycles, –30–90 °C	Up to 100 × 300 cm ²	Supply: 80–220 Vac, Power: < 5 W/m ²	Suspended particle device (SPD)
American Glass Products Company, AGP Europe GmbH, Ruhralle 9D, 44139 Dortmund, GERMANY Tel.: +43 231 9525 286 agpeurope@agpglass.com, http://www.agpglass.com/	VARIO Plus Polar	-	0.79–0.49	-	~0	-	100 000'nds operations, –20–65 °C	Maximum width: 1.1 m	110–220 Vac, 16 W/m ²	Suspended particle device (SPD) Hazing from 8 to 95%	Suspended particle device (SPD)
PLEOTINT L.C.C., 7705 West Olive Road, West Olive, MI 49460, USA Tel.: +1 616 738 8540; fax: +1 616 738 7661 info@pleotint.com, www.pleotint.com	VARIO Plus Sky	-	0.50–0.04, 0.40–0.01, 0.10–0.01	-	~0	-	-	Maximum width: 1.0 m	110–220 Vac, 5 W/m ²	Suspended particle device (SPD)	Suspended particle device (SPD)
Innovative Glass Corporation, 130 Newton Road Plainview, NY, USA Tel.: +1 516 777 1100; fax: +1 516 777 1106 info@innovativeglasscorp.com, www.innovativeglasscorp.com	Sunlight Responsive Thermochromic SKI	-	0.54–0.04	-	-	-	-	-	-	Thermochromic device	Thermochromic device
SPD Smartglass™	-	1.6	0.50–0.01	-	0.01	-	–30–90 °C	260 × 488 cm ²	120 Vac, 16 mA/m ² , 1.9 W/m ²	Suspended particle device (SPD)	Suspended particle device (SPD)

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