

Optical switching technology for glazings

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Abstract

The technology of optical switching devices for dynamic glazings and other applications is discussed. The status of the state of the industry and its developments is detailed. The technical emphasis will be on the properties of chromogenic materials covering electrochromic, phase-dispersed liquid crystals and dispersed-particle systems. Such technologies can be used for dynamic control of solar energy through building and vehicle glazings. Both visible and solar control can be obtained from these devices. Switching ranges can be from as high as 80% to 5–10% transmittance in the visible region. The energy and daylighting benefits of such glazings are discussed. Also, chromogenic glazings can be used for other product applications such as the modulation of reflector surfaces and large electronic information display systems. The science of selected electrochromic devices is covered. Technical issues concerning large-scale chromogenic devices are discussed.

1. Introduction

Optical switching technology is probably one of the most exciting areas in glazings and has the potential to change the view of a glazing as a fixed element to a dynamic element [1–3]. There are various physical optical techniques that can be used for the regulation of incident solar energy, daylight and glare in buildings and vehicles. Optical switching devices can be used for windows in a variety of applications where optical and thermal modulation is required. The purpose of this material is to control the flow of light and heat into and out of a window, according to personal comfort or an energy management scheme. The basic property of an optical switching material or smart window is that it shows a large change in optical properties upon a change in light intensity, spectral composition, temperature, electrical field or injected charge. This optical change results in a transformation from a highly transmitting state to a partly reflecting or absorbing state, either totally or partly over the solar spectrum.

The physical phenomena of interest for optical switching processes can be classified in one of two categories, either discrete mass movement or collective physical movement. Discrete mass movement includes ion and localized electron motion as seen in photorefractive, photochromic, electrochromic and thermochromic materials. Collective physical movement includes dispersed and homogeneous liquid crystals, and suspended particles, deformable membranes and adjustable diffraction gratings. All these processes are called “chromogenic” [4]. In this study we shall cover chromogenic switching processes including electro-

chromism, dispersed liquid crystals and suspended particle devices.

One of the most significant issues of this technology is the relationship between benefit, cost and lifetime. Much of this is not very well defined yet. The range of potential switchable window costs has been estimated to be US\$100–1000 m⁻² (US\$10–100 ft⁻²). Current glazing research is aimed at long-life devices with durability similar to regular coated windows. Related issues for all electrically activated devices are the quality and cost of transparent conductors, which are a large portion of the device cost [5, 6]. Commonly, Iridium tin oxide (ITO) In₂O₃:Sn and SnO₂:F. are used as conductors. Asahi Glass (Yokohama, Japan) has been advancing the quality and size of ion-assisted sputtered ITO-coated glass (over 2 m² with low haze and 1 Ω/□). There is considerable development on the production of low-resistivity ITO and ZnO transparent conductors onto plastic and glass substrates at low temperatures using ion-assisted evaporation [7, 8]. Advances have been made with the chemical vapor deposition (CVD) coating of glass on the float line with tin oxide at both Libby–Owens–Ford and Pilkington Glass companies. It is expected that these developments will help to reduce the cost of switchable glazings.

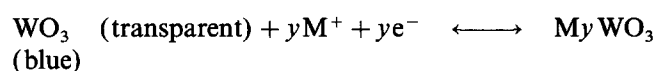
2. Chromogenic technology

2.1. Electrochromic materials and devices

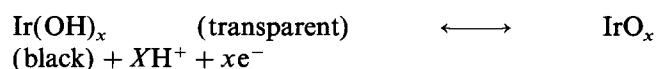
Electrochromic windows are a very popular area of chromogenic technology. Over the last 10 years, about 200 US and international patents have been granted per

year. The strongest commercial activities are found in Japan, Europe and the USA. Electrochromism is of current research interest because of its application to optical switching windows and mirrors for buildings and vehicles, large-scale electronic information display devices and eyeglasses. The major advantages of electrochromic materials are that (1) they only require power during switching, (2) they have a long-term memory (12–48 h), (3) they require a small voltage to switch (1–5 V), (4) they are specular in all states and (5) they have potential for large-area fabrication.

Electrochromic materials change their optical properties owing to the action of an electric field and can be changed back to the original state by a field reversal. There are two major categories of electrochromic materials: transition metal oxides including intercalated compounds, and organic compounds (including polymers). The electrochromic effect occurs in inorganic compounds by dual injection (cathodic) or ejection (anodic) of ions (M) and electrons (e^-). A typical reaction for a cathodic coloring material is



where $\text{M} \equiv \text{H}^+, \text{Li}^+, \text{Na}^+, \text{Ag}^+$ etc. A typical anodic reaction is



The inorganic materials that have gained the most research interest are various forms of WO_3 , NiO , MoO_3 and IrO_x . These compounds, among other transition metal oxides, have been the subject of several technology reviews [9–13]. An electrochromic device must use an ion-containing material (electrolyte) in close proxim-

ity to the electrochromic layer as well as transparent layers for setting up a distributed electric field. Devices are designed in such a way that they shuttle ions back and forth into the electrochromic layer with applied potential. A solid state window device can be fabricated from five (or less) layers consisting of two transparent conductors, an electrolyte or ion conductor, a counterelectrode and an electrochromic layer. Depending on the components used in devices, some of the layers can be combined to serve dual functions. Ion conductors and solid electrolytes also require further development for this technology. The most promising ion conductors are certain immobile solvent polymer systems, ionic glasses and open channel metal oxide structures such as perovskites. Typical electrochromic device structures developed by industry and university groups are given in Table 1.

Organic electrochromics are based on the viologens, anthraquinones, diphthalocyanines and tetrathiafulvalenes. With organic compounds, coloration is achieved by an oxidation–reduction reaction, which may be coupled to a chemical reaction. The viologens are the most studied of the organic electrochromics. Originally, organic electrochromics tended to suffer from problems with secondary reaction during switching, but recently more stable organic systems have been developed. The Gentex Co. (Zeeland, MI) and Donnelly Co (Holland, MI) have both commercially developed organic electrochromic materials for automotive mirrors. Mirrors are the most commercially developed electrochromic product to date. Gentex has made over 1 million mirrors over the last few years. The next area of development is in sun-roofs and visors. There are efforts at Sony and Sharp in Japan and IBM in London to develop a multicolor display screen using organic elec-

TABLE 1. Electrochromic device structures made by selected research groups

Electrochromic layer	Ion conductor or electrolyte	Ion storage	Maker
a- Li_xWO_3	$\text{LiClO}_4 + \text{PC}$	Redox Cple/ NiO	Asahi
a- WO_3	Ta_2O_5	$\text{Ir}_x\text{Sn}_y\text{O}_2:\text{F}$	Nikon
a- Li_xWO_3	$\text{LiClO}_4 + \text{PC}$	Prussian Blue	Nissan
a- H_xWO_3	Polymer	Polyaniline	Toyota
a- H_xWO_3	$\text{SiO}_2/\text{metal}$	WO_3	Schott
Viologen	PMMA + organic	None	Gentex
a- WO_3	Ta_2O_5	a- IrO_2	EIC
c- WO_3	Li-B-SiO Glass	IC/ $\text{Li}_x\text{V}_2\text{O}_5$	EIC
a- WO_3	Li-PEO	CeO_x	St. Gobain
a- Li_xWO_3	PPG-LiClO ₄ -MMA	$\text{Li}_y\text{V}_2\text{O}_5$	Chalmers University
a- H_xWO_3	Ta_2O_5	NiO	Donnelly
a- WO_3	Li-PEO	NiO	St. Gobain
NiO	a-PEO copolymer	$\text{Nb}_2\text{O}_5, \text{WO}_3:\text{Mo}$	LBL
a- WO_3	a-PEO copolymer	Polymer	LBL
Polyaniline	HCl		University of Rhode Island

a, amorphous; c, crystalline; PC, polycarbonate; PMMA, poly (methyl methacrylate); PEO, poly (ethylene oxide); IC, ion conductor; PPG, poly (propylene glycol); MMA, methyl methacrylate.

trochromics. New techniques for the electrodeposition of polymer electrochromics from solution have been reported by Toyota of Japan [14]. Uniform films of polythiophene, polyaniline and polypyrrole have been deposited by this oxidation polymerization technique. Polyaniline has recently become one of the favored organic polymer electrochromics [15, 16].

Much of the current activity on electrochromic windows is for automotive applications such as sun-roofs. This is an ideal entry market because of the smaller size and shorter lifetime required of the window, although the upper temperature limits are higher (90–120 °C, according to desert static soak temperatures for cars). Several research groups are investigating electrochromic materials and devices. Asahi Glass (Yokohama, Japan) has been steadily developing prototype electrochromic windows (0.3 m × 0.3 m) for testing and evaluation. Studies at Lawrence Berkeley Laboratory (LBL) evaluated the thermal and daylight control properties of these windows using the MoWiTT mobile window test facility [17]. Energy performance data is shown for a 0.9 m × 0.9 m matrix of Asahi electrochromic windows compared with a bronze single-glazed window in Fig. 1. The electronically controllable window has a considerable cooling energy advantage over that of a conventional bronze window. In this test the daylight illumination level inside the test chamber was regulated by the window to a constant value. Energy modeling of

electrochromic windows has shown that electrochromic windows can provide significant energy performance improvement compared with conventional double-glazed windows [18].

The Asahi window uses Li^+ ions for coloration of amorphous WO_3 , with a redox couple as part of the electrolyte [19, 20]. The optical response of this window is shown in Fig. 2. The problem of the use of liquid electrolyte has been reduced by using UV or thermally curable acrylic polymer as a binder. About 200 (0.4 m × 0.4 m size) prototype electrochromic windows have been installed in the Seto Bridge Museum (Kojima, Okayama-Prefecture, Japan). The use of polymer electrolytes opens possibilities of exploiting the benefits of adhesiveness, making for a safer and stronger window. It is possible to construct the device with two separate glass or polymer substrates. Other groups have developed polymer electrolyte electrochromic devices incorporating tungsten oxide [21, 22] and Prussian Blue [23]. Tungsten devices have been made with polymer-based ion storage layers at LBL [24]. The characterization and testing of electrochromic glazings are being carried out under an International Energy Agency Program (under Tasks 10 and 18) [25, 26]. A different approach is the development of low-cost limited-life switching devices based on plastic substrates. Southwall Technologies (Palo Alto, CA) has produced electrochromic electrodes of tungsten oxide/ITO on polyester.

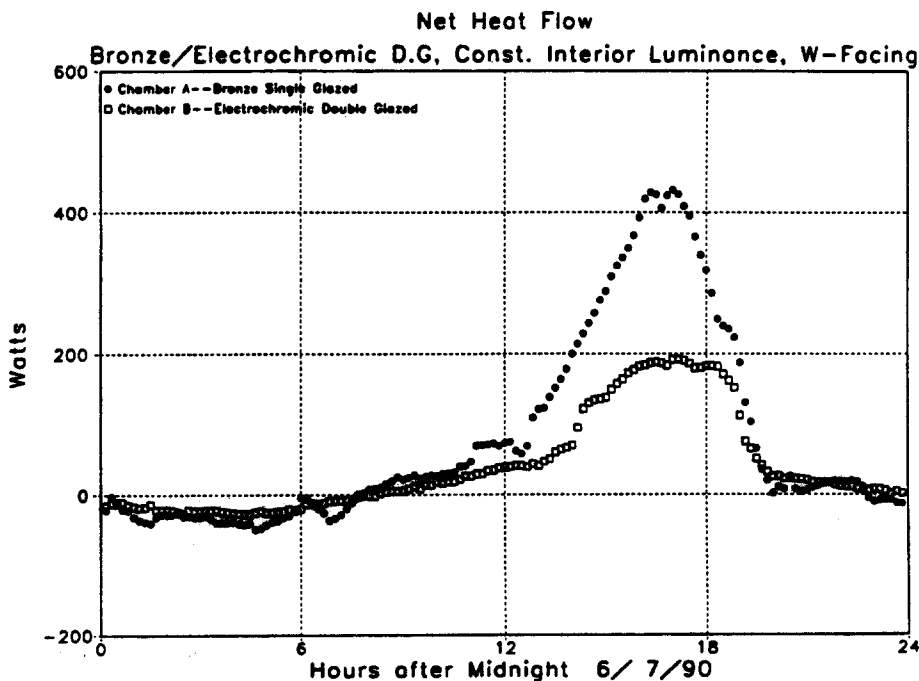


Fig. 1. Energy performance data is shown for a 3 × 3 matrix of 30 cm × 30 cm Asahi electrochromic windows compared with a bronze single-glazed window.

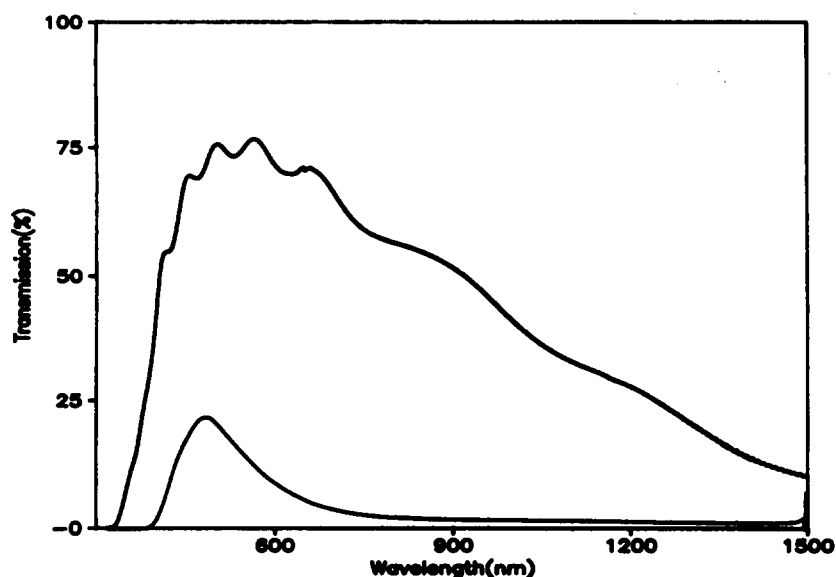


Fig. 2. Solar transmittance of an Asahi electrochromic window based on tungsten oxide, using a lithium polymer gel electrolyte. Both the bleached (upper curve) and the colored (lower curve) conditions are shown. Solar transmittance T_s , 53–10% visible; (photo-optic) transmittance T_v , 72–20%; 0.7 to 2 V.

Crystalline WO_3 offers near-IR modulation, which has the potential to control the IR portion of the solar spectrum. Crystalline WO_3 is being researched by several investigators [27–29]. Peak near-IR switching levels from 20% to greater than 75% was achieved with crystalline tungsten oxide [30]. The reflectance properties of tungsten oxide films produced so far seem to lie rather far from the theoretically limiting behavior. Research has been conducted on plasma-enhanced CVD deposited amorphous MoO_3 and WO_3 aimed at increasing coating deposition rates [30]. Also, there is considerable research into the deposition of tungsten oxide coatings using atmospheric CVD, much like the on-line coating of tin oxide.

Electrochromic NiO is being developed by several groups [31–35]. Nickel oxide devices using a polymer electrolyte are also being studied at LBL, among other groups [36]. Nickel oxide has been coupled with manganese oxide, cobalt oxide and niobium oxide in all alkaline devices [37]. An example of the optical response of an electrochromic NiO/polymer/ Nb_2O_5 device is shown in Fig. 3. A nickel oxide/tungsten oxide in truck mirror has been commercialized by Donnelly and Optical Coating Labs, Inc. (Santa Rosa, CA). Pilkington with European partners under the 1990–1993 European Community program are also involved in electrochromic materials development.

There are many other candidate electrochromic materials, primarily among the transition metal oxides and among several classes of organic compounds. In fact, the study of “unconventional” inorganic or organic electrochromic materials will be a fertile area for re-

search and development for years to come. Also, the development of ion storage layers for tungsten and nickel devices is one of the most active and difficult areas of research. Several stringent materials requirements for thin and thick films makes electrochromic devices a very challenging subject for the materials scientist, thin films engineer and physicist. The overall thermal performance of these windows is very dependent on the window design and placement of the layers. In an actual design to obtain the maximum benefit from the window, low emissivity layers may be required for thermal insulation purposes.

2.2. Liquid crystal devices

Liquid-crystal-based systems offer another approach to chromogenic electrically activated devices. The basic classes of liquid crystal light switching devices are the twisted nematic guest–host, surface-stabilized ferroelectric and polymer-dispersed liquid crystals (PDLCs). The mechanism of optical switching in liquid crystals is to change the orientation of liquid crystal molecules interspersed between two conductive electrodes with an applied electric field. The orientation of the liquid crystals changes with the field strength that alters the overall optical properties of the device [38–40]. Open-circuit memory is not possible with liquid crystals. The most widely used type for electronic displays is the twisted nematic type [41, 42]. For windows, the twisted nematic type is not a good choice since it requires polarizers that reduce transmission and have fabrication size limitations, because of stringent gap spacing requirements. Twisted nematics have been used for

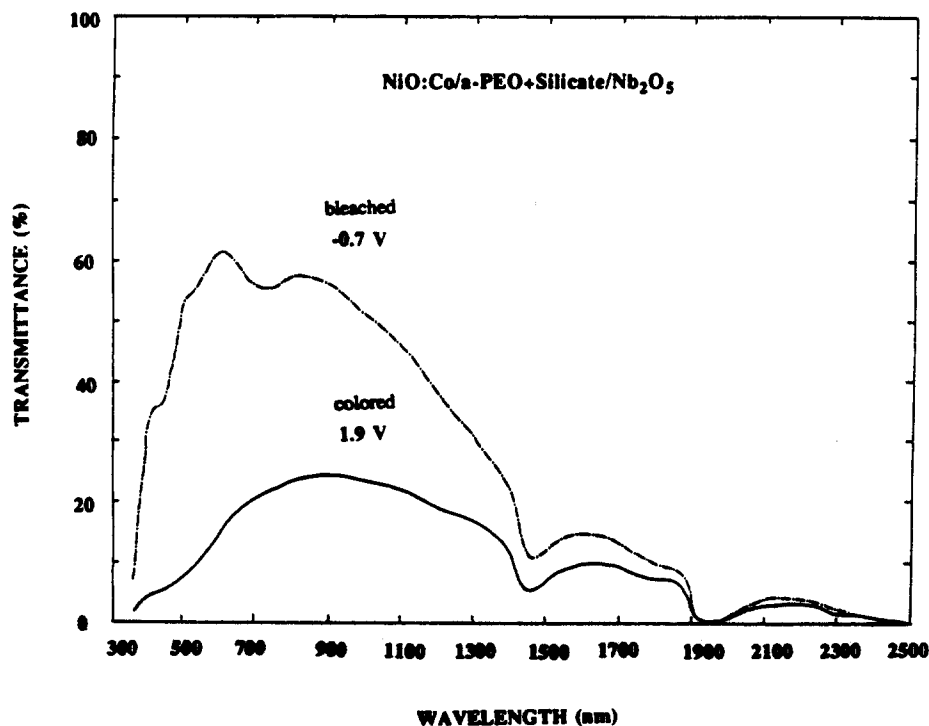


Fig. 3. Solar transmittance of an LBL nickel oxide/niobium oxide electrochromic device using a laminated polymer ion conductor. This device colors to a deep bronze.

electrically controlled welding goggles made by Optrel AG (Wattwil, Switzerland). Recently considerable work has been done on surface stabilized ferroelectric liquid crystals. These are being developed for electrooptic switches by Displaytech Inc (Boulder, CO). They are bistable and switch in 0.15 ms with ± 15 V d.c. but unfortunately exhibit high contrast ratios (about 50) in a narrow temperature range. They are very difficult to manufacture. With further improvements in the liquid crystal it is expected that this type will become more useful.

The guest–host and PDLCs are the best choice for large-area glazing. The guest–host types use dichroic dye molecules mixed with liquid crystals [43]. The guest–host type is being developed mainly for display applications [44]. The cholesteric–nematic phase change guest–host type of liquid crystal has the greatest chance of being used for large-area optical switching. This type of liquid crystal switches by a field-induced phase change. It exhibits a continuous gray scale operating from 20 to 120 V a.c. with a contrast ratio of 5:1 and uses no polarizers. The upper temperature stability is 100 °C. Guest–host liquid crystal devices are being developed by Asulab in Switzerland for eyeglasses and car mirrors. A car mirror based on this technology can switch visible reflectance $R_v = 48–12\%$ with switching times of 15 and 360 ms for

on and off respectively. This has been possible with the development of improved UV and electrochemical stability of the liquid crystals by Mitsui Toatsu Chemicals, Japan, and E. Merck, Germany.

The PDLC or encapsulated liquid crystal (nematic curvilinear aligned phase (NCAP) consists of nematic liquid crystals distributed in microcavities [45]. This cavity structure can give modulated light scattering known as the Christiansen effect. PDLC and NCAP materials have very similar characteristics but are defined in the patent literature differently according to the preparation procedure. NCAP films are formed from an emulsion and PDLC films are formed from an isotropic solution which phase separates during curing. General Motors Research Laboratories (Warren, MI), 3M (St. Paul, MN) and Kent State University (Kent, OH) have developed PDLC technology for automotive glazing [46]. The typical solar and photopic transmission and reflectance hemispherical values for a PDLC device are $T_{s(\text{off-on})} = 53–77\%$, $R_{s(\text{off-on})} = 20–14\%$, $T_{v(\text{off-on})} = 48–76\%$ and $R_{v(\text{off-on})} = 27–18\%$.

Devices based on NCAP technologies were produced by Taliq (Sunnyvale, CA) as optical shutter materials for glazings and information displays (known as Varilite and Vision Panel). Nippon Sheet Glass markets this product in Japan as the “Umi” Device. At least two other major companies in the USA are developing NCAP automotive sun-roofs. Large-area devices have

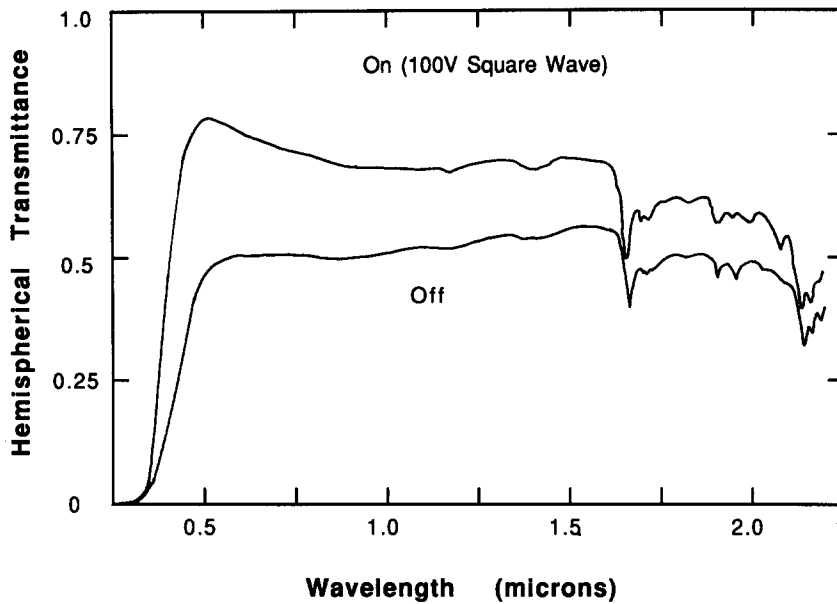


Fig. 4. Hemispherical transmittance of an undyed dispersed liquid crystal window film (Taliq). Both the fully transparent (on at 100 V) and the fully scattering (off at 0 V) states are shown.

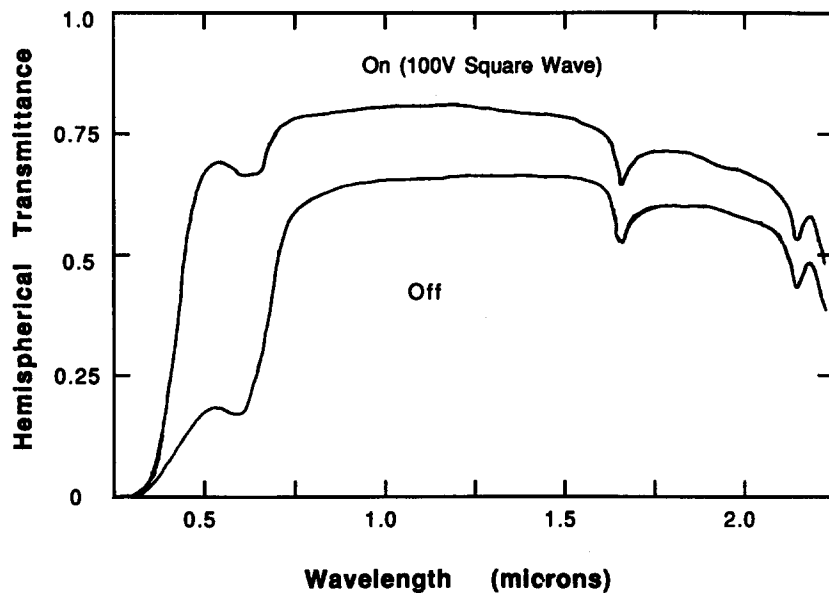


Fig. 5. The hemispherical transmittance properties of a dyed dispersed liquid crystal window made by Taliq. Both the fully transparent (on at 100 V) and the fully colored scattering (off at 0 V) states are shown. The color is gray.

been fabricated in $1\text{ m} \times 2.5\text{ m}$ sheets. With NCAP the liquid crystals are encapsulated within an index-matched polymer matrix. The composite polymer is fabricated between two sheets of ITO-coated polyester that serve as electrodes. The device can also be fabricated between one sheet of glass and one sheet of plastic or two sheets of conductive glass. The switching effect of this device spans the entire solar spectrum, up to the absorption edge of the glass. In the off state, the device appears translucent white. Since the off state in

these devices is diffusely transmitting, the device has application for privacy and security. An example of its optical properties is shown in Fig. 4. The hemispherical transmittance property of a dyed NCAP device is shown in Fig. 5. The dyed film shows considerable control over visible transmittance compared with the undyed film in Fig. 4. When an electric field is applied, the liquid crystal droplets align with the field and the device becomes transparent [47]. Typically these devices operate between 50 and 100 V a.c. (potentially 20 V in

the future) at less than 20 W m^{-2} but require continuous power to be clear. Pleochroic dyes can be added to darken the device in the off state [48]. In general, compared with electrochromics, the power consumption is higher because of the need for continuous power in the activated state. Dispersed liquid crystal devices have a very good future but are restricted by three characteristics: the unpowered state is diffuse, haze remains in the activated (transparent) state and UV stability is poor. Many of the devices made to date are used in interior building applications. The residual haze problem can probably be alleviated by better control over the formation and processing of the liquid crystal emulsion. The UV stability is being improved. For widespread use of NCAP and PDLC devices the cost will have to decline.

2.3. *Suspended-particle devices*

The development of suspended-particle or electrophoretic devices has spanned many years. Some of the earliest work was done by Edwin Land of Polaroid in 1934. The development of suspended-particle devices has been slowed by a number of technological problems including long-term stability, cyclic durability, particle settling and agglomeration, and gap spacing control for large areas. In recent years, many of these problems have been reduced or controlled [49–51]. Commercial development of these devices for eyeglasses, goggles and windows is being done by Research Frontiers, Inc. (RFI) (Plainview, NY) and its licensees. A group of 50 RFI windows ($0.46 \text{ m} \times 0.46 \text{ m}$) have been installed as a demonstration in the Japan Steel Works Building (Fuchan, Japan). Gloverbel S.A. (Brussels, Belgium) is working to develop mirrors and windows for cars. Other groups working on this technology are Litton Systems Canada for visors, and Hankuk Glass Industries (Korea) and Nippon Sheet Glass for glazings and Northern Engraving for automotive displays [52].

A suspended-particle device consists of three to five layers. The active layer has needle-shaped particles of polyiodides (dihydrocinchonidine bisulfite polyiodide) or paraphathite ($1 \mu\text{m}$ long) suspended in an organic fluid or gel. This layer is laminated or filled between two parallel conductors. In the off condition the particles are random and light absorbing. When the electric field is applied, the particles align with the field, causing the transmission to increase. Typical transmission ranges are 20–60%, 10–50% and 0.1–10%, with switching times of 100–200 ms. The voltage required for the device depends on the thickness and ranges from 0–20 to above 150 V a.c. An interesting version of this technology is being developed by Nippon Sheet Glass in Japan. They have combined particles inside a polymer droplet [53]. A sheet form of the dispersed-particle glazing may be available in the future.

3. Conclusions

Chromogenics embraces a fascinating mix of basic work and applications which ultimately may lead to better buildings and vehicle glazing, and display technology. In a number of applications, it will help lower the demands on precious non-renewable fuels for lighting and cooling. The prospects are great and so are the scientific and technological challenges of large-area chromogenics. Electrochromic devices were compared with dispersed liquid crystals and suspended-particle devices. One of the significant costs for all devices is the transparent conductors. It is expected that with further development of lower cost deposition processes this cost will decline. There are several promising electrochromic devices for window glazings. For the electrochromic layer, tungsten trioxide, nickel oxide and viologens are the most developed for devices. In the future, the developments will lie in the designing of the appropriate ionic and electronic materials to make devices durable over the long term. PDLC devices have a good future but are limited by three characteristics: the unpowered state is diffuse, haze remains in the transparent state and UV stability needs improvement. The residual haze problem can probably be alleviated by better control over the formation and processing of the liquid crystal emulsion. The UV stability will have to be improved, but this is possible too. The development in dispersed-particle devices is moving forward with a number of commercial activities and demonstration. These devices are colored in the off state and become transparent in the on state. With further improvements in processing and the development of a sheet form of this material, these devices could see widespread use. Durability is of obvious importance for many large-area chromogenic devices, and sometimes an expected lifetime of at least 5–15 years must be assured. However, chromogenic devices are emerging in a few products and it is expected their application will redefine our concept of the window and large-area display technology.

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