Abstract - Several companies throughout the world are developing dynamic glazing. University and National Laboratory groups are researching new materials and processes to improve these products. The concept of a switchable glazing for building and vehicle application is very attractive. Conventional glazing only offers fixed transmittance and control of energy passing through it. Given the wide range of illumination conditions and glare, a dynamic glazing with adjustable transmittance offers the best solution. This study covers selected electric powered switching technologies including electrochromism, suspended particles, and encapsulated liquid crystals. Also, the study covers thermotropic glazing. Examples of markets including buildings, vehicles and aerospace are given. Also, examples of installed switchable glazings are shown. This dynamic glazing technology creates many opportunities and challenges for future solar designers.

1. INTRODUCTION

This paper will cover certain selected electric powered switchable glazing and thermotropic technology and markets. The markets covered for switchable windows are buildings, automotive and aerospace. This paper updates earlier papers on chromogenics [Lampert, 1998, Lampert, 1999].

Chromogenics [Lampert and Granqvist, 1990, Seeboth, 2000] have some unique properties that have not been seen in other products for glazing. Electrochromics behave as a thin film battery that shows its state of charge optically. Electrochromics can be switched on demand or even have a self-powering feature. They exhibit memory in any state. Electrochromics are favored for many applications because when they switch they remain specular, and non-scattering. This means they can be used for a variety of view or see-through applications. They can be easily powered because of their low voltage. Either direct DC or batteries or solar cells can supply power to electrochromic glazing. Suspended particle devices (SPD) behave in the opposite way to electrochromics, they are more absorbing or scattering in the off-state compared to the on-state. However, the SPD has an advantage of having much lower scattering in the off-state compared to polymer dispersed liquid crystals. With SPD’s viewability remain even in the off-state. Polymer dispersed liquid crystals (PDLC’s) can not be used for this unless the application tolerates this, like upper windows and skylights. But, PDLC’s are sold on their unique privacy properties for security windows, utility vehicle side windows, and office privacy dividers. Thermotropics are sold for light control to restrict overheating in buildings. Thermotropics are used for skylights, inclined windows and upper windows in non-view areas.

Commercial switchable products are used for several different applications. Electrochromics are used for automotive mirrors, made by Gentex (Zeeland, MI), Donnelly (Holland, MI), Toyota (Japan), Nikon (Tokyo, Japan), Murakami-Kaimedo (Japan) Electrochromic medium-scale architectural windows are made by Pilkington/Flabeg (Germany), and skylights by Schott-Donnelly, (Tucson, AZ) and SAGE/Viracon (Faribault, MN), PDLCs are made for privacy glass by Nippon Sheet Glass (Japan). In the near-future, we expect to see electrochromic vehicle sunroofs (Schott-Donnelly, Tucson, AZ), SPD vehicle sunroof (Research Frontiers Inc., NY) and aircraft passenger windows (Saint-Gobain, France). Thermotropics are being commercialized by Interpane and Affinity with Asahi Glass. In the more distant future, we expect to see large-area architectural windows, and vehicle glazing. Almost all of these devices rely upon vacuum deposition either for transparent conductors or device elements. Sometimes, different processes such as sol-gel, chemical vapor deposition and screen printing are used to make all or portions of switchable glazing and display devices.

2. APPLICATION MARKETS

2.1 Architectural

Architectural applications have dominated the research and development of switchable windows. The flat glass market for architectural glazing is one the most attractive. There are wide possible applications in a variety of buildings. The use of flat glass is very wide spread, the world production of flat glass is about 2.4 billion m$^2$ per year, for all markets, with the largest portion going to building and automotive glazing. Window production in the U.S. alone is over 400 million m$^2$/yr. The types of switchable glazing
products for buildings are: windows, residential insulated glass units (IGU), skylights, inclined glazing, security windows, commercial glazing, sunroom glazing, interior specialty glazing, and doors. The major drawback in the development of switchable windows has been their size and lifetime requirements of 10-30 years. Several companies have undertaken the development of switchable windows. Pilkington/Flabeg (UK/Germany) have introduced their “E-Control™” switchable glazing in Europe.

2.2 Vehicles
Chromatic technology has a very important place in future vehicle glazing. It continues to be one of the most exciting topics in automotive glazing. The technology can dynamically change how the transmittance of the sunroof, side and back glazing, tint band, visor, and mirror Chromogenic technology can make an interior very comfortable and adjustable according to the driver’s needs and changing visual environment. This technology can provide greater safety by virtual elimination of glare and reflections, which can fatigue or frustrate the driver.

The application to automotive glazing is probably nearer to market because the sizes are smaller than commercial windows and the lifetime is less (7 years is the average lifetime). Dynamic glazing systems can be totally automatic or semi-automatic or manual switching capabilities. The demand for switchable sunroof glazing is growing. The most largely successful product is the electrochromic automotive mirror. Switchable mirrors are available for most major makes of cars. The chief manufacturers are: Gentex (Zeeland, MI), Donnelly (Holland, MI) and Nikon (Japan) licensees. Prototypes of electrochromatic automotive sunroof and glazing panels have been shown by Schott-Donnelly, Flabeg, and Saint-Gobain. Prototype automotive SPD panels have been shown by Hankuk Glass (Korea). Hankuk is a licensee of Research Frontiers Inc. (RFI). (Woodbury, NY) [Yu, Kim, Lee, 1997].

2.3 Aerospace
The aerospace field is interested in the development of visors and windows that can control glare for pilots and passengers. Early work was done by PPG (Pittsburgh, PA) on electrochromic cockpit side windows. Several prototypes were shown at air shows, but the product was discontinued. Also, in early work done on aircraft glazing. Dornier part of the Daimler-Chrysler Aerospace group (Germany), made prototype glazings for aircraft cockpits. They showed a 0.3 x 0.3 m size laminated tungsten oxide/ polyaniline prototype electrochromic window. Daimler-Chrysler Aerospace has announced dimmable windows for their first class cabin of the new Airbus Industrie model A3XX airplane to be on the market in about 2003-2004. Over the next 20 years there will be about 35% replacement of the aging aircraft on the world market. Also, the aircraft stock will grow from 13,000 in 1999 to 28,000 planes in 2018 [Boeing, 1999]. It will be interesting to see how many new aircraft will be equipped with switchable glazing or even energy efficient glazing. Saint-Gobain has publicly shown their prototype electrochromic Airbus cabin windows [Betelle, Boire, and Giron, 1999]. These windows have a 40:1 contrast ratio with the deeply colored visible transmittance less than 1%. Chemically tempered and bent glass is used to satisfy the safety requirements for aircraft glazing.

3. ELECTROCHROMICS

3.1 Properties of Electrochromics
Electrochromic devices are the most popular technology of large-area switching devices. Much of the electrochromic technology is being developed for building windows and automotive mirrors and windows. The major advantages of electrochromic materials are: (1) they only require power during switching; (2) have a small switching voltage (1-5 V); (3) are always specular; (4) have gray scale; (5) have low polarization, (6) many designs have adjustable memory, up to 12-48 hr. Typical electrochromic glazing devices can have upper visible transmission of \( T_v=70-50\% \) and fully colored transmittance of \( T_v=25-10\% \). Levels of transmittance as low as 1% are possible. The range of shading coefficients for electrochromic glazing (SC) is about \( SC=0.67-0.60 \) for the bleached condition, and \( SC=0.30-0.18 \) for the fully colored condition.

Electrochromic materials change their optical properties due 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)[Lampert, 1984]. The electrochromic effect occurs in inorganic compounds by dual injection (cathodic) or ejection (anodic) of ions (\( Li^+ \)) and electrons (\( e^- \)). An example electrochromic reaction for a cathodic coloring material using lithium as a coloration ion is:

\[
WO_3 (\text{colorless}) + 0.3Li^+ + 0.3e^- \leftrightarrow Li_0.3WO_3 (\text{blue})
\]

A complimentary anodic lithium nickel oxide reaction is:

\[
Li_{0.3}NiO_2 (\text{gray})- 0.3Li^+ - 0.3e^- \leftrightarrow Li_0.2NiO_2 (\text{colorless})
\]
These reactions show by using two different materials, composed of one layer that colors upon intercalation and one that colors on deintercalation, both sides of the device can color at the same time giving high optical density. Depending on the electrochromic, various coloration ions can be used, such as: Li⁺, H⁺, Na⁺, and Ag⁺. The binary inorganic oxides have gained the most research interest are: WO₃, NiO, MoO₃, V₂O₅, and IrOₓ [Granqvist, 1995, Granqvist, 2000]. Tungsten oxide is the most understood of all the oxides [Bange, 1999]. Many times these materials are written as idealized stoichiometric compounds, when the best performance occurs in non-stoichiometric ternarys and quarternary analogues. An electrochromic device must use an ion-containing material (electrolyte) in close proximity 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. An electrochromic glazing can be fabricated from five (or less) layers consisting of two transparent conductors, electrolyte or ion conductor, counter electrode, and electrochromic layer as shown in Figure 1.

Fig. 1. Schematic of an electrochromic showing the layers of the device (not to scale). The construction is similar to a battery.

Depending on the components used in devices, some of the layers can be combined serving dual functions. Some devices use even more layers depending on design. The most promising ion conductors are certain immobile solvent polymer systems, ionic glasses and open structure metal oxides.

Organic electrochromics are based on the viologens, anthraquinones, diphthalocyanines, and tetrathiafulvalenes [Monk, 1995]. 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 and used commercially of the organic electrochromics. Originally, organic electrochromics tended to suffer from problems with secondary reactions during switching, but more stable organic systems have been developed. Gentex has developed liquid organic electrochromic materials for automotive mirrors.

### 3.2 Electrochromic Products

Electrochromic mirrors are designed to automatically regulate glare in response to incident light levels. Both the Gentex Co. and Donnelly Co. have commercially developed electrochromic materials for automotive mirrors. Mirrors are the most commercially developed electrochromic products to date. The UV levels and upper temperature requirements are high for automotive sunroofs (95-100 °C) making this application challenging. The industry projected selling price goals for electrochromic glazing are within the 100-250 US$/sq. m. range. However, most prototypes are a factor of ten higher in cost.

Pilkington Deutchland/Flabeg has shown several prototype “E-Control™” switchable glazing of 0.80 m x 1.6 m. installed in buildings. The window has a transmittance range of Tᵥ=50-15% [Becker and Wittkopf, 1998]. The spectral transmittance is shown in Figure 2 for bleached and maximum colored conditions. This is in an insulated glass unit-using two panes of glass including low-emittance coatings.

Fig. 2. Transmittance of Pilkington Deutchland/Flabeg IGU E-Control™ electrochromic double glazing. The bleached condition is shown as squares and the colored condition is shown as triangles

A group of E-Control™ windows covering 8 x 17 m has been installed in the Stadtsparkasse Bank in Dresden, Germany. The glazing takes a few minutes to change color or to bleach. An example of an electrochromic glazed wall is shown in Figure 3.
In France, St. Gobain is working to develop a range of electrochromic devices for a variety of applications. In Japan, Asahi Glass and Nippon Oil have been steadily developing electrochromic windows of 1 sq. m based on Li_xWO_3/Li-polymer/Carbon stripes for testing and evaluation. This glazing had monochromatic transmittance, T_{633 nm} = 60-19% [Kobo, Toya, Nishikitani, and Nagai, 1998].

Fig. 3. South facing view of 8 x 17 m of electrochromic EControl™ glass made by Pilkington Deutchland/Flabeg. Installed in the Stadtparkasse Dresden am Altmarkt. (Source: T. Deinlein, Flabeg GmbH)

Another type of electrochromic design is the nanocell structure. This type actually is fashioned from the nanocell photovoltaic cell so the electrochromic can self-color when exposed to sunlight. The cell relies on a dye sensitized anatase titanium oxide layer which forms distributed p/n junction. Its optical density can be regulated by resistively shunting the anode and cathode of the cell. Schott-Donnelly, NREL and the EPFL group have developments on this form of photovoltaic.

OCLI (Santa Rosa, CA) sold their electrochromic technology to AFG Glass. AFG is in the process of commercializing a switchable window technology. Schott-Donnelly has announced a “Ucolite™” circular dimmable skylight for use with light pipes for daylighting in buildings. An example of a rectangular skylight made by Schott-Donnelly is shown in Figure 4. The visible transmission properties can be varied from about 70-15% in 1-2 minutes. SAGE working with Agpoe Enterprises has developed electrochromic glazing. Early this year, SAGE showed a SageGlass™ switchable skylight product at the National Association of Home Builders 2000 Show (Dallas, TX). An example of that skylight is shown in Figure 5. The window size is about 1 x 0.6 m. Prototype SAGE windows have about a visible switching range of 70-4%.

Fig. 4. Electrochromic skylight made by Schott-Donnelly, shown in the bleached and colored condition, T_v = 70-15% (Source: A. Agrawal, Schott-Donnelly)

Fig. 5. Electrochromic Skylight made by SAGE Corp. (Source: M. Myser, SAGE, website:www.sage-ee.com).
3.3 Electrochromic Research

The International Energy Agency (IEA) has investigated electrochromic materials and devices for building windows. There are several European government-funded programs. One of the bigger multinational projects is the Joule Commission of the European Communities (CEC) project. This project finished in 1998. Pilkington PLC (UK) had a multiyear project electrochromic glazing under the JOULE II program. This project involved several organizations, including Flachglas/Pilkington Deutchland and Davionics AS (Denmark), Oxford Brookes University and the University of Southampton. Participants in the Eureka EC project are the Granqvist group at the University of Uppsala (Sweden) working with Coat AB (Sweden) and Leybold AG (Germany). In France, St. Gobain, Corning Europe, and C.S.T.B and the University of Domaine are working with electrochromic devices and components. In Italy, there are several groups involved in electrochromic devices testing and development.

The Japanese Government’s, Sunshine project, which funded part of Asahi's past work. The project goals were to develop electrochromic glazing with 50 % variable change; 10 year projected lifetime and high cycle lifetime. For this glazing the Asahi group has obtained optical properties of $T_v=73-18\%$ and $T_s=55-11\%$ withstanding 100,000 cycles at 60 C. This device was based on the all-inorganic device structure. The current Asahi/Nippon Mitsubishi Oil project is to make laminated electrochromic windows using a carbon stripe geometry.

Sustainable Technology Inc. (STI) (Australia, web site: www.sta.com.au) is developing electrochromic windows with the help of the National Government Dept of Energy (ERDC). They have research partnerships with University of Technology-Sydney, Dept. of Physics, Monash University (Australia) and The Institute for New Materials (Saarbrucken, Germany, web site: www.inn-gmbh.de). STI uses solgel deposition to produce their films on glass. STI uses a lithium salt loaded polymer for their ion conductor.

Under the U.S. DOE (Dept. of Energy, web site: www.usdoe.gov) Electrochromics Initiative. Several organizations are funded to develop electrochromic glazing including Schott-Donnelly, SAGE and Eclipse Energy (Gainsville, FL). Eclipse Energy is developing PECVD deposited electrochromics using the National Renewable Energy Labs (Golden, CO, website:www.nrel.gov) (NREL) patents. The Lawrence Berkeley National Laboratory (LBNL) has developed building energy models to quantify energy saving of electrochromics (web site:www.eetd.lbl.gov/btp). NREL has been given the job of evaluating the lifetime and durability of electrochromic devices for the US National Program.

4. SUSPENDED PARTICLE DEVICES (SPD)

The development of suspended particle or electrophoretic devices and glazing has spanned many years. Edwin Land of Polaroid in 1934 did some of the earliest work on electrophoretic devices. Interestingly, RFI has just announced licensing their SPD technology to Polaroid. We are beginning to see versions of SPD technology being applied to electronic paper. A suspended particle device consists of 3-5 layers. The active layer has needle shaped dipole particles (<1 mm long) suspended in an organic fluid or gel. This layer is laminated or filled between two electrical 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 increased transmission. Typical transmission ranges are 20-60%, 10-50%, 0-10%, with switching speeds of 100-200 ms. The voltage required for the device depends on thickness and ranges from 0-20 to above 150 V a. c.

RFI and their licensees are responsible for the commercial development of SPDs for goggles, eyeglasses and windows. Recent activities have been directed at polymer sheet development. Several companies have licenses with RFI for the development of specific products. Recently Hitachi Chemical and Dai Nippon Ink have licensed process to make ink and emulsion for devices. Two commercial groups working with RFI are Hankuk Glass (Korea) and Materials Research Corp. (San Diego, CA). Their product focus is architectural and automotive glazings.

Toyota Labs (Japan) has developed a new type of dispersed particle window. By modification of the particles, several colors (green, blue, red, and purple) can be achieved [Tacheuchi, 1996]. These developments are beginning to make this technology that has been developed over 20 years much more viable for large-area glazing application. New submicron dipole suspensions based on SiO$_2$ coated TiO$_2$N$_x$ have been developed by Nippon Sheet Glass [Saito, et al, 1998]. With this particle up to 50% change in solar transmittance has been shown.
5. PHASE DISPERSED LIQUID CRYSTALS (PDLC)

Common types of liquid crystals are nematic, smectic, twisted nematic, cholesteric, guest-host, and ferroelectric. For displays, twisted nematic liquid crystals are the most commonly used liquid crystal. The mechanism of optical switching in liquid crystals is to change the orientation or twist of liquid crystal molecules interspersed between two conductive electrodes with an applied electric field. The orientation of the liquid crystal can alter the overall optical reflectivity properties of the window or display.

One fairly unusual version of a liquid crystal system is to make an emulsion of a polymer and liquid crystal to form a film. This emulsion is called phase dispersed liquid crystals (PDLC) [Montgomery, 1990] or nematic curvilinear aligned phase (NCAP) [van Konyenbergen, Marsland and McCoy, 1989] has been commercialized for use in switchable glazings. There are some preparation and structural differences between PDLC and NCAP, but here they will be treated without distinction since their performance is similar. The liquid crystals are encapsulated within an index matched polymer matrix. The polymer emulsion is fabricated between two sheets of transparent conductor coated polyester or glass that serves as electrodes. The switching effect of this device spans the entire solar spectrum, up to the absorption edge of glass. In the off-state, the device appears translucent white. When an electric field is applied, the liquid crystal droplets align with the field and the device becomes transparent.

Typically these devices operate between 60-120 V a. c. (potentially lower in the future). Their power consumption is less than 20 W/m² but require continuous power to be clear. In general, compared to electrochromics, the power consumption is higher for liquid crystals because of the need for continuous power in the activated state. The typical integrated hemispherical visible transmission values for a PDLC device are $T_v^{(off-on)} = 50-80\%$. The shading coefficient changes by $SC=0.63-0.79$. Pleochroic dyes can be added to darken the device in the off-state. The dyed film shows considerable control over visible transmittance compared to a non-dyed film.

Open circuit memory is not possible with dispersed liquid crystals, without added dipoles to sustain the particle orientation. NEC and Toyota Labs (Japan) have developed a method to sustain the liquid crystal orientation after the external field is removed.
accomplish this by the introduction of a dipole particle that retains its local field. The device requires two separate frequencies to switch on or off. By this technique Toyota has achieved 20 hours of memory for a PDLC device [Kawasumi, et al, 1996]. Improvement in PDLCs have been made by Rohm and Haas by lowering the switching voltage and off-angle haze [Clickerman and Roebling, 1996].

Raychem (Sunnyvale, CA), now part of Tyco, licenses NCAP processes to Isoclima (Italy), St. Gobain and Nippon Sheet Glass (NSG, Tokyo, Japan). NSG produces a PDLC product known as "Umumu" for specialty automotive and building applications. Large-area PDLC glazing can be fabricated in 1 m x 2.5 m sheets. Open circuit memory is generally not possible with dispersed liquid crystals. However, by adding dipoles to the liquid a memory effect can be achieved. Some of the issues that remain are UV stability and cost, which is about 750-950 US$/sq. m. for glazings.

6. THERMOTROPICS

Thermotropics have been studied and developed for glazing. These materials exhibit large physical changes about certain design temperatures. They will appear clear at lower temperatures, but change to an opaque film at higher temperatures. In the opaque condition they are highly light scattering. These materials can be used for skylights, inclined glazing and upper windows where view is not important. They can be totally passive, changing with ambient temperature change or solar heating. Some designs use a resistive heating layer made from thin metals or transparent conductors to artificially heat the gel layer to make it switch. The thermotropics scatter light like the PDLC materials, however the PDLC’s tend to be more isotropic scatterers. Most thermotropics are based on hydrogels and for higher temperature performance polymer blends have been studied. A example of a thermotropic polymer gel is polyether/ethylene oxide/carboxyvinyl. The gel switches from transparent to translucent with increasing temperature. It has privacy characteristics in the switched state.

Some early work was done by Suntek (Albuquerque, NM), on "Cloud Gel" an example of a hydrogel film laminated between two glazings. Another group at the Fraunhofer Institute for Building Physics (Stuttgart, Germany) studied what they called "TALD" hydrogel glazing. A later product was developed under a joint project between Interpane with BASF and the Fraunhofer Institute for Solar Energy Systems, (Freiburg, Germany. The Interpane film has optical characteristics of $T_v(25-60C)=79-4\%$ and $T_s(25-60C)=63-3\%$ with $R_v(25-60C)=8-49\%$ and $R_s(25-60C)=7-39\%$. [Wilson, 1994, Wilson et al, 1995]. Affinity Corp. (Tokyo, Japan) has developed a similar hydrogel glazing which has been licensed to Asahi Glass. [Watanabe, 1998]. The technical problems with the hydrogels are UV stability, cyclic lifetime, and inhomogeneity during switching. These are under development at BASF.

7. CONCLUSIONS

Chromogenics have unique properties for applications for large-area glazing. In this study selected technologies were covered including electrochromics, dispersed particles, electrophoretic displays, encapsulated liquid crystals. A table of comparative technology is shown in Table 1. Electrochromics are favored for many applications because when they switch they remain specular, and non-scattering. This means they can be used for a variety of view or see-through applications. They can be easily powered because of their low voltage. Electrochromics have been commercialized for automotive mirrors. Fairly large windows have been shown and installed in buildings by Pilkington/Flabeg, and Asahi Glass. Other companies are working on the introduction of glazing products for automotive sunroof applications. Production cost and process simplification are major issues for large-area electrochromics. Suspended particle devices (SPD) are more absorbing in the off-state compared to the on-state. SPDs have an advantage of having much lower scattering in the off-state compared to PDLC’s. Also, SPD’s can be made to have a neutral color. SPDs can be made into a flexible sheet form so they can be used in a variety of applications. Research Frontiers Inc., Hankuk Glass of Korea and Materials Research Corp. are working hard to produce a flexible product in the near-term. Hankuk has shown prototypes of displays, sunroofs and architectural windows. The cost is expected to be considerably lower than PDLCs. PDLCs are sold for their unique privacy properties for security windows, and office privacy dividers. PDLC can be made in a flexible sheet form, but are limited to mainly interior applications because of UV stability problems. The chief maker of PDLC panels is Nippon Sheet Glass. Thermotropic glazing is poised to become commercial if all the stability issues can be overcome. Glazing is being developed at Interpane with BASF and the Fraunhofer Institute for Solar Energy Systems and at Affinity working with Asahi Glass. The future holds some exciting developments in displays and windows.
Table 1. Comparison of Chromogenic Glazings

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Note: Typical values are underlined, some upper values reflect research values.

REFERENCES


