Materials for Good Day-Lighting and Clean Air: New Vistas in Electrochromism and Photocatalysis

Claes-Göran Granqvist
The Ångström Laboratory, Uppsala University, Uppsala, Sweden

Presented at the 50th SVC TechCon in Louisville, KY, in the Smart Materials session on May 2, 2007

Abstract
Modern vacuum coatings offer many possibilities to accomplish energy efficiency and indoor comfort in buildings. This paper presents a number of ideas based on electrochromic (EC) thin film devices for modulating the transparency of visible light and solar energy in “smart windows” and points out that the same technology can be used for energy efficient day-lighting based on the notion of balancing the lighting from windows and from light-guides to obtain an even illumination level in extended spaces. The possibilities of EC foil devices are emphasized; they are inherently cheaper and have wider application ranges than the more traditional glass-based devices. The paper also presents some novel ideas to use windows for air cleaning applications by taking advantage of solar driven photo-catalysis. Most importantly, perhaps, the paper stresses the role of vacuum coating technology to produce much needed energy savings in the building environment.

Introduction: The Challenge
The imminent dangers of global warming are no longer in need of an introduction, and means to alleviate these dangers clearly are of the greatest urgency. The risks are in no way hypothetical: for example, it has been stated that the warming and precipitation trends due to anthropogenic climate change during the past thirty years already claim over 150,000 human lives annually [1,2]. These changes are also expected to be accompanied by more common and/or extreme events such as heatwaves, heavy rainfall, and storms and coastal flooding. There is also a possibility that nonlinear climate responses will lead to even more rapid climate changes such as breakdown of ocean “conveyor belt” circulation, collapse of major ice sheets, and/or release of large quantities of methane at high latitudes thus leading to intensified global warming [3].

Furthermore, the much needed advances in energy technology must take place for an increasing population, whose growing concentration in mega-cities leads to “heat islands” which tend to aggravate the warming [4] and can lead to an increase of the urban cooling load by up to 25% compared to the case of the surrounding rural areas [5]. By 2050 there will be some ten billion people in the world. Energy must be available to them all, and it has to be clean. New technologies are necessary to accomplish this. This paper regards a number of such technologies related to transparent building envelopes capable of combining energy efficiency and good day-lighting, and with possibilities to clean indoor air. Vacuum coatings are essential in this context.

A focus on the building environment is natural, and within the EU(15), about 40% of the energy is used for heating, cooling, lighting, and ventilation [6]. Not surprisingly, the European Commission, in its Action Plan for Energy Efficiency of 2006–20, states that:

“... Too much energy continues to be wasted in buildings because of inefficient heating and cooling systems... certain new phenomena also contribute to the rise in our energy consumption, such as increasing air conditioning...”

Indeed the energy demand for air conditioning has grown at a frightening pace, amounting to about 17% per year in the EU [7]. Already today electrically driven air conditioning dominates the peak power during the summer in parts of Europe and the US; for Hong Kong and Singapore, about 50% of the peak power goes into air conditioning, and in the extreme climate of Kuwait the corresponding number is a stunning 75% [8].

Why this increase? The answer is growing demand on indoor comfort. Part of this demand lies in a lack of acceptance of thermal discomfort due to too high or too low temperatures; another reason is found in the wish for good indoors-outdoors contact via large windows and glass facades. So large glazed areas tend to give cooling problems, but small windows give bad indoor comfort and hence poor job satisfaction with ensuing poor job performance. One way to alleviate the situation is to have windows and glass façades with variable throughput of visible light and solar energy, i.e., “smart windows,” as discussed further below. The same technology can be combined with light-guiding technology and thereby open new possibilities for energy efficient day-lighting.

Forced ventilation is another cause for excessive energy expenditure. This is indeed not surprising since health-related problems resulting from the indoor air are issues of frequent public concern. Thus pollution of air inside buildings often leads to discomfort for the occupants and in some cases may even be a health hazard. Low air quality can result from poor ventilation, pollutants and micro-organisms from inadequately maintained ventilation systems, gaseous odours emitted from building materials, tobacco smoke, etc. The indoor air contains a wide range of volatile organic compounds (VOCs) with different chemical and physical properties. Over 900 chemical compounds have been detected in indoor air [9]. The concentration of these VOCs depends on type of activity in the rooms, ventilation rates, number of persons present, furniture, etc. A number of these VOCs have a higher concentration indoors than outdoors [10], as highlighted by a recent EU study [11]. Exposure to VOCs has been suggested to cause the Sick Buildings Syndrome, a diverse affliction that includes symptoms like mucous irritation (e.g., irritation of the eyes, nose, and throat), skin irritation as well as odour and taste complaint, neurotoxic effects (e.g., fatigue, lethargy, headache, nausea as well as reduced memory and concentration), and non-specific reactions (e.g., chest sounds and asthma-like symptoms) [12,13]. Later in this paper we introduce solar-energy-driven photo-catalysis—again using transparent building envelopes—as a possible new technique for energy-lean air cleaning.

Before proceeding one should realize the magnitude of the market for windows and glass façades, taken here to be the market for flat glass. The world production is 4.3 Bm²/y (dominated by Asia), the value is 7.7 B$ (2010) and the annual growth is 5.9%. Concerning use, 37% is in domestic buildings, 23% is in commercial buildings, and 27% is in vehicles of various kinds.

Chromogenic Technology for Building Envelopes with Variable Transmittance
There are different “chromogenic” technologies and associated materials for achieving variable transmittance [14]. Perhaps the most well
known material is photochromic glass for sun goggles. However, such glass changes its transmittance too slowly for windows use, and it does not provide acceptable solar control. Another technology uses thermochromic coatings based on vanadium dioxide (VO₂) which lower their transparency as the temperature goes up. The modulation of the solar inflow is too small, though, and it has been difficult to achieve sufficient luminous transmittance, and hence this technology has severe limitations. Electrochromic (EC) technology avoids the problems inherent in photochromics and thermochromics and allows user control by the application of electrical current when the optical properties are to be changed [15,16].

A systems perspective is necessary in order to fully benefit from the EC technology. Looking, specifically, at an office module equipped with sensing of physical presence, the control—in a wireless fashion—can be effected in at least three different ways: (i) on-site operator control, (ii) control to comply with a pre-programmed “comfort profile” with adjustment to the user’s individual preferences, and (iii) automatic energy minimization when the room is not in use. The philosophy is hence to allow the user of the room to decide when he or she is present, but to let the control system take over when the room is not in use. In short, the window should be transparent/dark depending on whether there is a heating/cooling need and if the room is in use or not. This control strategy, which may seem obvious enough, is covered by patents.

The energy savings inherent in the “smart windows” technology has been much discussed during the past several years. The most detailed investigation so far has been reported in work for the California Energy Commission [17]. The summary of this report states that:

“Switchable variable-tint electrochromic windows preserve the view out while modulating transmitted light, glare, and solar gains and can reduce energy use and peak demand. [...] Compared to an efficient low-e window with the same day-lighting control system, the electrochromic window showed annual peak cooling load reductions from control of solar heat gains of 19-26% and lighting energy use savings of 48-67% when controlled for visual comfort. Subjects strongly preferred the electrochromic window over the reference window, with preferences related to perceived reductions in glare, reflections on the computer monitor, and window luminance.”

The strong decrease of the energy for lighting is noteworthy and perhaps at first sight surprising. It will be possible to increase these savings still further by use of a new day-lighting strategy, for which a patent is pending, which combines EC technology with facilities to direct day-light deeply into buildings by use of light-guides. By equalizing the light level in a room, the eye—which tends to adjust to the brightest illumination—does not perceive deeper regions as disturbingly dark, and hence there is less need for artificial lighting. Similar notions, though employing a Venetian blind system, have been discussed earlier [18,19]. Generally speaking, the EC technology leads to new vistas in day-lighting, which is generally regarded as superior to artificial lighting by giving better task performance, improved visual comfort, and positive mood effects, especially if glare problems are eliminated [20]. Particularly beneficial effects have been observed concerning improved student performance in day-lit schools [21] and increased sales in day-lit stores [22].

**Electrochromic Foil and its Manifold Uses**

Figure 1 illustrates an EC device—specifically an EC foil—and its drive circuitry [16]. The foil embraces two PET foils, each with a two-layer coating, which are laminated together. The central part is an EC layer based on tungsten oxide (WO₃) and another EC layer based on nickel oxide (NiO) joined by an adhesive polymer electrolyte. Surrounding continued on page 50
this stack are transparent electrical conductors normally based on tin-doped indium oxide (In$_2$O$_3$:Sn, also known as indium tin oxide or ITO) [23,24]. Applying a voltage between the ITO layers, charge can be transferred from the NiO to the WO$_3$, and then both oxide layers get dark; applying a voltage in the opposite direction (or short circuiting) transfers charge from WO$_3$ to NiO and then both of these layers become transparent. Since all of the other components of the laminated foil are transparent, it is evident that the overall transparency is altered. It is instructive to consider the EC foil as a “thin film electrical battery” whose charging state manifests itself in optical absorption.

The EC device has a number of features that make it particularly well suited for window applications—which of course motivates the positive assessment in the report to the California Energy Commission referred to above—viz. (i) the voltage needed to change the transparency is only of the order 1 to 2 V dc (easily obtained from solar cells), (ii) the voltage needs to be applied only when the optical changes are made implying that energy is not wasted simply to keep the optical properties constant, (iii) the transmittance can be tuned gradually and reversibly between widely separated extrema and can be set at any level between the two endpoints, (iv) the color in the dark state is neutral gray so that the foil does not lead to distorted color renderings, (v) the visual appearance is haze free, and (vi) the materials in the EC foil do not have adverse health effects.

The EC foil can be used in several different ways in future fenestration technology as well as for day-lighting purposes. One of these options is illustrated in Figure 2. More generally, the EC foil can be used as follows: (i) suspended in double-glazed units thus creating lightweight “third window panes,” (ii) mounted onto existing glazings in the same manner as conventional “window films” and hence, importantly, adequate for retrofitting existing windows, and (iii) the entire foil can be used as a lamination material for joining two window panes thus creating spall-free “safety glass” suitable for e.g. high rise buildings.

Figure 3 shows recent characteristic data for a 5 x 5 cm$^2$ flexible EC foil incorporating WO$_3$, NiO modified by addition of a wide band gap oxide such as MgO or Al$_2$O$_3$, PMMA-based electrolyte, and ITO films [16,25-27]. The mid-luminous transmittance ($T_{550}$ where the subscript denotes wavelength in nanometers) rapidly attains ~68% upon bleaching and drops to ~36% during a coloration period of 50s. Still lower values can be reached with extended coloration times. The open circuit memory is excellent, and the optical properties are maintained virtually unchanged for many hours.

EC technology is sometimes perceived as inherently expensive, a view that is supported by the price of today’s EC “products” (typically sold on a limited scale with a price of ~1000 $/m$^2$). Another use for EC glass is in sun roofs for some top-of-the-line cars. The belief that the technology must be expensive is wrong, though, given the right materials and manufacturing techniques. Figure 4 indicates a low-cost roll-to-roll technology. The following items are of particular relevance: (i) the coating technology is based on reactive dc magnetron sputtering which is the same technique as the one used today for coating window panes up to 30 m$^2$ in size, (ii) charge insertion/extraction in the oxide films is done via facile gas treatments [28,29] suitable for mass production, (iii) lamination is done via a continuous process, and (iv) cutting to size and contacting are feasible from a semi-infinite web.

It may be of interest to compare with thin film solar cells which are much in vogue today; they are much more expensive per area unit than the EC foil for the simple reason that the coatings are much thicker than in the EC foil.
In Figure 5 the upper panel illustrates a “smart windows” prototype with four 30 x 30 cm² panes equipped with EC foil and set so that two panes are in their dark state and two panes are in their fully bleached state, while the lower panes shows a variable-tint visor for safe and comfortable motorcycle riding.

Why it has taken so long to get to today’s EC technology. One answer is that it hinges on a number of non-standard techniques, each of one with its specific challenges, which must be mastered for success. Among these techniques one may note: (i) making highly conducting and highly transparent ITO films, which is not an easy task especially if the substrate does not allow high temperatures as in the case of PET; excellent ITO can be made on PET, though, with sufficient knowledge and experience on narrow ranges of process parameters, (ii) the EC films of WO₃ and NiO must have carefully controlled nanoscale porosities and be uniform over large surfaces, which calls for non-

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standard sputtering technology; (iii) the polymer electrolyte must combine good ionic conductivity, excellent adhesiveness, extreme ultraviolet transparency, and chemical compatibility to WO₃ and NiO; (iv) the introduction/extraction of accurately controlled amounts of electrical charge into WO₃ and NiO must take place under conditions allowing mass production; and (v) the electronic unit (cf. Figure 1) is a key to long-term durability and its design is of the greatest importance.

**Air Cleaning Windows Using Solar Driven Photo-catalysis?**

Photo-catalytically active surfaces can cause breakdown of organic molecules as well as microorganisms adsorbed on these surfaces under the action of solar irradiation [30,31]. Thus hazardous or otherwise unpleasant pollutants can be decomposed into tasteless, odorless, or at least less toxic compounds. Numerous oxides are well known to exhibit photo-catalytic properties, with most work having been devoted to TiO₂ with anatase type crystal structure. This oxide is able to work with UV light only owing to the width of the band gap. The photo-catalytically active surfaces normally are comprised of nanocrystalline structural units.

Deodorization is possible, which in principle allows the use of natural light, rather than some energy-consuming air cleaning device, to purify indoor air. Recent work in this area has been reported for VOCs [32-36] and for numerous other gases. TiO₂ coatings are also active for photo-catalytic breakdown of bacteria [37-39]. Photo-catalytic surfaces are usually backed by glass or metal, but coatings onto flexible PET, having a protective surface layer of SiO₂, has demonstrated photo-catalytic elimination of trichloroethylene [40]. Coated fluorocarbon foils have also been studied recently [41].

It may be an advantage to employ not only UV light but also the less energetic but more abundant visible light for photo-catalysis, and many different dopants have been added to TiO₂ for that purpose in order to modify the spectral absorption range. The photo-catalytic surfaces exhibit photo-induced super-hydrophilicity, meaning that water droplets spread more or less evenly over the surface so that light scattering tends to be insignificant. Thus the water is not visible and, furthermore, drying-related contamination residues do not appear, which can be a considerable asset from a practical point of view. Most studies have been made on films coated onto glass substrates, but PC substrates have been studied recently too [42].

Figure 6 illustrates a patented idea to use a double-pane window as a photo-catalytic reactor. The outer pane is ultraviolet-transparent and can be comprised of iron free (“super clear”) glass, whereas the inner pane has a TiO₂-based coating on the side facing the air gap. If room air flows between the panes, it can be cleaned by photo-catalysis.

**Conclusion**

This paper has presented some novel ideas for using coated glass or PET to provide energy efficiency jointly with a comfortable indoor climate in the building environment. It is believed that work along these lines will be able to decrease the current practice of energy use in many buildings and thereby to some extent contribute to meeting “the Terawatt challenge” [43].

Ending with some speculations, membrane architecture [44,45] may in the future be merged with EC foil technology in order to allow light-weight buildings with little embodied energy. These notions are perfectly in tune with concepts such as “intelligent buildings” [46] and “smart skins” [47]. One can envisage huge membranes allowing the flow of visible light and solar energy to be controlled and optimized. The possibilities offered by such membranes—although then based on glass technology—were pointed out more than fifty years ago by the great visionary Buckminster Fuller [48]. Perhaps this grand vision will come true one day thanks to electrochromics.
References


Claes-Göran Granqvist has been Professor of Solid State Physics at the Department of Engineering Sciences, The Ångström Laboratory, Uppsala University, Sweden, since 1993. He was formerly Professor of Experimental Physics at Gothenburg University, Sweden, in 1989–1993. Granqvist’s research during the past several years has covered materials, mostly PVD-deposited thin films, for energy efficiency and solar energy applications particularly in the built environment. Variable-transmit- tance “smart” windows is one example, which also forms the basis of ChromoGenics Sweden AB, a company founded by Granqvist and his collaborators and presently employing some 15 persons. Other research interests include nano-science and sensor science. Granqvist has published more than 630 scientific papers and many books and proceedings volumes. He has an Honorary Doctorate from UNI (Lima, Peru), is Fellow of SPIE, is honorary member of the Indian Materials Society, and member of the Royal Swedish Academy of Science and The Royal Swedish Academy of Engineering Sciences.

For more information, contact Claes-Göran Granqvist at claes-goran.granqvist@angstrom.uu.se.