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Citation for the original published paper (version of record):

Granqvist, C G., Bayrak Pehlivan, I., Niklasson, G A. (2018)
Electrochromics on a roll: Web-coating and lamination for smart windows
Surface & Coatings Technology, 336: 133-138
<https://doi.org/10.1016/j.surfcoat.2017.08.006>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

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<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-348848>

Electrochromics on a Roll: Web-Coating and Lamination for Smart Windows

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Abstract

Electrochromic devices can vary the throughput of solar energy and visible light in glazing for buildings, which are then able to combine improved energy efficiency with enhanced indoor comfort and convenience. The technology can be implemented in different ways; here the focus is on web-coated devices which can be delivered, on a roll or in the form of large sheets, as foil for glass lamination. The present paper introduces the technology, discusses web-coating *versus* in-line glass coating, mentions lamination, and touches on possibilities to combine electrochromism with other functionalities such as thermochromic control of solar energy transmittance. The purpose of the paper is to give a tutorial overview of a technology that is currently introduced in buildings.

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1. Introduction

The emission of carbon dioxide and other greenhouse gases into the atmosphere due to human activity increases the global surface air temperature and sea level, disrupts weather patterns, and acidifies the sea [1]. Solutions to this energy–environment conundrum include decarbonizing energy production and enhancing energy efficiency [2], and doing this while economic growth is sustained [3] and serves a population that is burgeoning [4] and increasingly agglomerated in urban centers [5]. Buildings are essential in this context and are responsible for 30–40% of the World’s current use of primary energy [6].

There are many, often untapped, opportunities for energy saving in the built environment [7], frequently related to “green” nanotechnologies [8], and electrochromic (EC) glazing (windows and glass facades) is an important one. This technology [9–11] enables electrical regulation of the throughput of solar energy and visible light and yields energy efficiency by evading unnecessary cooling and heating of indoor air [12,13] as well as enhanced human comfort and convenience for the building’s occupants by preventing glare and thermal discomfort [14]. Importantly, these improvements are accomplished without imperiling the glazing’s primary function: to provide unimpeded visual indoors–outdoors contact as well as daylighting.

Buildings are built to last for decades or centuries, and EC technology must be highly durable, reliable and affordable, which calls for rugged device design and appropriate technology for mass fabrication. This paper introduces the essentials of EC technology and discusses how it can be implemented with web-coating in conjunction with glass lamination. Examples of installed EC glazing are presented, and emerging possibilities to accomplish also temperature-dependent switching of energy flows are outlined. Some prior results on web-coated EC-based devices—or single coatings of interest for EC technology—can be found in the scientific literature [15–19].

2. Electrochromic technology: Basics

An EC glazing can be viewed as an electrical thin-film battery whose degree of charging is related to optical transparency, and the two types of devices largely share the same assets and idiosyncrasies. Fig. 1 illustrates a generic EC device design with five superimposed layers between transparent substrates [20].

Fig. 1. Principle design of a web-based EC device. Small arrows indicate ion transport upon application of a low voltage between the transparent electrical conductors. The foil can be used for glass lamination, as indicated in the left-hand part.

The central component of the EC device conducts ions but is an insulator for electrons. It is usually a polymer electrolyte layer or a transparent inorganic ion-conducting coating; the mobile ions are normally protons (H^+) or lithium (Li^+). The ion conductor is in contact with an EC coating exhibiting both ionic and electronic conductivity. Tungsten oxide (WO_3) is the premier example of an EC material [21,22] and is widely used in today's EC glazing [10]. The other side of the ion conductor is in contact with an ion-storage coating, which also conducts ions and electrons. The ion storage coating may exhibit EC properties, as in the example depicted in Fig. 1. The three-layer stack is located between two coatings of transparent electrical conductors which in principle can be of different kinds [10,23] but in practice often consist of an oxide based on tin or indium. Applying a voltage, typically a few volts dc, between the transparent conductors yields ion transport between the EC coating and the ion-storage coating, and the displaced charge is balanced by electrons inserted into or extracted from the EC coating and the ion-storage coating via the transparent conductors. These electrons are the cause of optical transmittance changes in the EC coating. Reversing the voltage, or in some cases by short-circuiting, regains the original optical properties. EC devices may have open-circuit memory, which makes them highly energy efficient, and their optical transmittance can be set at any intermediate level between fully colored and fully bleached. The voltage should be applied via busbars at the circumference of the EC device in

order to enable even distribution of charge and minimize geometry-dependent differences in the optical properties; this voltage may be supplied by photovoltaics [24]. A square-meter-size EC glazing may take minutes or more to transition between fully colored and bleached states, which is a desirable feature and permits the eye to light-adapt.

It is appropriate to use an EC ion-storage coating with optical properties complementary to those of the primary EC coating, and devices combining tungsten-oxide-based and nickel-oxide-based coatings [25–27] are often employed in EC glazing [10]. Moving charge from nickel oxide (known as an “anodically coloring” EC material) to tungsten oxide (with “cathodic coloration”) makes both coatings dark, and both coatings bleach when charge is returned. Fig. 2a shows spectral transmittance for an EC device according to Fig. 1, and Figs. 2b and 2c indicate that the tungsten oxide and nickel oxide coatings darken predominantly within separate wavelength ranges in the luminous spectrum (400–700 nm), the net effect being that the color approaches neutrality [20,28]. Color properties as well as durability can be boosted in mixed oxides, and recent work has demonstrated particularly good properties for tungsten–titanium–molybdenum oxide [29].

(a)

(b)

(c)

Fig. 2. (a) Spectral transmittance of an EC foil device according to Fig. 1 subjected to the shown charge transfers, and analogous data for the (b) tungsten-oxide-based and (c) nickel-oxide-based parts of the foil.

3. Electrochromic glazing: Web coating *versus* glass coating

The EC device design, introduced above, can be implemented in glazing in more than one fashion, and products are marketed internationally or regionally by at least four vendors. The traditional manufacturing technique is to have the EC coatings deposited by reactive magnetron sputtering onto glass panes pre-coated with transparent conductors, whereas the electrolyte is either a thin coating—made by physical vapor deposition or chemical deposition from vapor or gel—or a layer prepared by injecting the electrolyte in the space between the two coated glass panes. In the former case, it is possible to deposit sequentially, in a single process, all five layers of the EC device thus making a monolithic device, which is noteworthy for its large optical modulation span. Another manufacturing technique—which is in focus here—uses plastic web rather than glass as a substrate for the EC coatings. The

plastic web is usually of polyethylene terephthalate (polyester, PET), which is a commodity product, but other plastics can be employed as mentioned below. This plastic-web-based design is illustrated in Fig. 1; the electrolyte is applied as a polymer gel and subsequently solidified by cross-linking. Typical optical properties of a web-based EC device are shown in Fig. 2.

The various ways to manufacture EC glazing yield several different characteristic features, but they may lead to products with similar optical properties and EC performance. Some of the distinguishing features are elucidated next:

- EC devices based on glass with typical thicknesses of several millimeters are much heavier than if plastic web, with typical thicknesses of some tenths of millimeters, is used, the weight difference being typically a factor one hundred, which obviously is important for the logistics of EC-based products, especially for transport over large distances.
- The EC device prepared by web coating must be integrated in an insulated glass unit (IGU), which can be achieved by conventional glass lamination typically using polyvinyl butyral (PVB) or ethylene vinyl acetate (EVA). This step can be done by, in principle, any glass laminator who delivers his product to, in principle, any IGU manufacturer. Thus a light-weight web-coated EC device can be produced at a location that is far removed from the site where the glazing is produced, which implies that business models for web-based and glass-based EC devices are radically different. The web-based product can be delivered on a roll or as large sheets to the laminator or IGU manufacturer, who then cuts out pieces in any desired size and shape, applies busbars, and finishes the glazing.
- A significant difference between EC devices based on glass and plastic web regards the busbars required for uniform charge transport and coloration. These busbars need to be applied to the coated glass pane prior to its incorporation in an IGU, whereas the busbar can be attached, reliably and conveniently, at any preselected position on a coated web.
- Having the electrolyte as a thin coating may be attractive from the perspective of coating technology and enable “monolithic” EC five-layer stacks that, at least in principle, can be made by in-line glass coating. There are hurdles, though, and pinholes in the electrolyte coating may give some electron transfer between the EC coatings. Such an EC device behaves as a battery with non-negligible internal leakage

current that tends to discharge the “battery” with ensuing loss of optical absorption. To keep the EC glazing dark then requires repeated electrical “refresh pulses”, which has bearings on energy efficiency and, perhaps, durability. Another implication of having the electrolyte as a thin coating is that the coated surface is highly delicate and needs protection in order not to be damaged, which implies that IGU manufacturing must be accomplished at the coating site.

- A polymer electrolyte allows convenient functionalization [30,31] to achieve additional properties both for web-based and glass-based products, as further discussed below.
- The plastic lamination material in a web-coated EC device can provide spall shielding upon breakage, burglar protection and acoustic damping.
- Web-coated EC devices can easily be applied onto bent glass.

Fig. 3 gives a schematic outline of manufacturing technology for web-coated EC devices. Panel (a) shows that the device comprises two layers of PET, which are supplied with transparent conducting oxide (TCO) layers and have two complementary (“cathodic” and “anodic”) EC coatings joined by an electrolyte layer. The TCO coatings are connected to a control unit for insertion and extraction of charge. Web coating and device assembly are illustrated in Fig. 3b and indicates sputter deposition of tungsten-oxide-based and nickel-oxide-based coatings as well as continuous lamination.

Fig. 3. (a) Principles of an EC device with complementary EC coatings on polyester (PET) web pre-coated with transparent conducting oxide (TCO). (b) Schematic manufacturing process implemented by reactive sputter deposition of tungsten oxide and nickel oxide onto web coated with indium–tin oxide (ITO).

Fig. 4 shows a practical installation of EC glazing based on web coating and depicts the interior of a room with two windows in fully dark state and a third pane fully transparent. The unimpeded indoors–outdoors view should be noted.

Fig. 4. Example of interior view of glazing based on web-coated EC devices.

4. Some futures aspects: Electrolyte functionalization

The polymer electrolyte layer in an EC device can be functionalized by incorporation of nanoparticles, which may boost the ion conductivity and therefore contribute to the optical

modulation dynamics and, more importantly, can lower the throughput of solar energy while the transmittance of visible light remains almost unchanged. This property is illustrated in Fig. 5, which shows that the luminous transmittance is high irrespective of the amount of indium–tin oxide (ITO) nanoparticles in an electrolyte layer, whereas the infrared part of the solar irradiation spectrum (700–2500 nm) is lowered in proportion to the amount of nanoparticles [30]. The infrared-blocking property is important since roughly half of the solar energy comes as radiation in this wavelength range, and consequently the solar energy throughput is strongly diminished. The nanoparticles were ~ 13 nm in size and small enough not to cause noticeable light scattering (“haze”). The optical properties of the ITO nanoparticles can be modeled quantitatively [32,33], as also indicated in Fig. 5.

Fig. 5. Spectral optical transmittance as a function of the quantity of indium–tin oxide nanoparticles (in weight percent) in a 70- μm -thick layer of a transparent polymer electrolyte based on polyethyleneimine-lithium bis(trifluoromethylsulfonyl) imide. Experimental data (curves) and calculated results (symbols) are reported.

An interesting possibility, which remains to be tested for glazing applications, is to use nanoparticles with properties that are thermochromic, i.e., different above and below a certain temperature in the neighborhood of room temperature. The most well-known thermochromic material is vanadium dioxide (VO_2) [34], which is semiconducting at low temperature and metallic-like at high temperature; the transition between the two regimes takes place around 68 $^\circ\text{C}$ in bulk VO_2 but is typically somewhat lower in a thin coating or in nanoparticles. If needed, the transition temperature can be decreased by adding a minor amount of tungsten to the VO_2 [35]. Fig. 6 shows optical transmittance for a thin coating of VO_2 and for a dilute

nanoparticle composite containing an equal amount of VO_2 . The most interesting properties are found for the nanoparticles, which clearly are able to diminish the throughput of solar energy at high temperatures whereas this radiation can be transmitted at low temperatures.

Fig. 6. Spectral optical transmittance (upper panels) and reflectance (lower panels) for a 50-nm-thick coating of VO_2 (left-hand panels) and for a layer consisting of a dilute dispersion of VO_2 nanospheres, having an equivalent VO_2 thickness of 50 nm, in a medium characteristic of transparent glass and polymer. Data pertain to low temperatures (semiconducting VO_2) and high temperature (metal-like VO_2).

5. Conclusions and outlook

Electrochromic glazing has come a long way since its infancy in 1984 [36,37] and has now (2017) been installed in numerous buildings particularly in Europe and the USA, where such glazing delivers energy efficiency jointly with indoor comfort and convenience. Low-cost manufacturing is one of the keys to successful products and, as discussed in this paper, web-coating can be applied to obtain light-weight and rugged electrochromic foil devices supplied as large sheets or on a roll ready to be used for glass lamination and integration in insulated glass units. Glass lamination and glazing production may be far removed from the manufacturing site for the electrochromic foil, which diminishes the need to transport heavy and breakable goods over large distances. The electrochromic coatings are typically tungsten-

oxide-based and nickel-oxide-based—as discussed above—but vanadium-pentoxide-based coatings can be used as well [38].

Whither electrochromic glazing? Predictions are precarious! However, multifunctionality may become an essential property, and it is feasible to invoke thermochromic control of solar energy throughput, as mentioned earlier. Other possibilities include electrochromics combined with energy generation [39] and energy storage [40] as well as “dual-band” electrochromics [41]. Photocatalytic purification of indoor air by use of short-wavelength (ultraviolet) solar irradiation is another option that is currently being explored in the context of glazing and where the increased temperature in an absorbing electrochromic coating is an asset [42,43].

So far the discussion has been focused on glazing literally based on glass. But this is not the only option for web-coated electrochromic devices, which may be employed without attachment to glass in innovative membrane architecture of a kind that already exists in sports stadiums, function halls and other light-weight constructions [44,45]. The membranes are made of transparent or translucent ethylene tetrafluoroethylene (ETFE), which is durable enough to last for many decades under full solar exposure. Coating the ETFE with ITO or some other transparent conductor is a critical step, but recent advances in coating technology [46] and in sub-second heat treatment of coatings on temperature-sensitive substrates [47,48] give clear indications that the technical challenges can be met so that web-coated electrochromic devices may be happily married to membrane architecture.

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