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Modeling of optical and energy performance of tungsten-oxide-based electrochromic windows including their intermediate states

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ABSTRACT

Tungsten-oxide-based electrochromic (EC) windows are currently the most robust and matured dynamic windows where the transmittance of visual light and near-infrared radiation can be controlled by a small applied voltage. In its standard application, the window is commonly either in its clear or colored state. In this contribution, we study the optical and energy performance of such window in the fully bleached and fully colored state as well as when it is kept in intermediate states. Different configurations in terms of placement of the EC layer stack and possible additional low-emissivity (low-*E*) coating within the insulated glass unit are considered. Using optical data and software tools we find that even a small coloration has a significant effect on the energy performance because the solar heat gain coefficient is readily reduced by the absorption of the EC layer stack. We compare the performance of the EC windows to commercially available solar-control (spectrally selective) low-*E* windows.

1. Introduction

The 2010 United Nations Environment Programme Annual Report stated that buildings consume more than one-third of the global energy [1]. Over the past decades, increasing attention has been given to the reduction of energy consumption in residential and commercial buildings. Windows are a critical component of the building envelope which can greatly improve energy efficiency of buildings. Windows should provide usable daylight and comfort to occupants. This implies that means are implemented which deal with discomforting glare while optimizing the use of daylight for lighting purposes. This could be done, for example, by shutters, blinds, or the later–discussed chromogenic window solutions. A window is expected to provide visual contact to the outside, which affects the type of window and shading device selected. For best thermal insulation, heat transfer through the window should be minimized, or better yet, controlled depending on environmental, occupational and other conditions. Reducing heat transfer is generally advantageous in both summer and winter conditions. One needs to reduce the solar heat entering the building under cooling conditions in summer. In winter, heat loss to the outside needs to be reduced. Those heat transfers involve very different parts of the electromagnetic spectrum, and require detailed consideration of the visible wavelength (380–780 nm), solar infrared (780–2500 nm), and near-room-temperature infrared (3–50 μm) radiations.

The two main measures of energy performance for windows are the *U*-factor and the Solar Heat Gain Coefficient (SHGC). The *U*-factor can be a measure of the heat transfer for either the complete window, including glass and framing components, or for the center-of-glass. It expresses the energy transfer per time, area and temperature difference between the inside and outside of a building, hence the unit $W/(m^2\,K)$. The *U*-factor describes the thermal insulating property of the window and is inversely proportional to the *R*-value, a common measure of thermal insulation in buildings. The *U*-value does not consider direct sunlight. This is accomplished by the SHGC, which is defined as the fraction of solar radiation (incl. the re-radiated portion of the absorbed solar radiation) which is transmitted through the window into the building [2]. Therefore all window properties, including gas fill and emittances of the glazing surfaces, will affect the SHGC. Besides energy performance in terms of *U*-value and SHGC, transmittance in the visible part of the solar spectrum is important to daylight illumination, reducing the need for artificial lighting, and to provide the above-mentioned visual contact to the outside world.

Since the late 1970s, the glass coating industry has invested huge efforts in improving the energy performance of windows [3], leading to insulated glass units (IGU) having at least two glass panes. Usually one of the glass panes has a heat-reflecting coating, also known as low-emissivity or "low-*E*" coating. Indeed, low-*E* windows have become the standard for energy efficient window

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technology, where the reduced emissivity is based on the presence of a transparent conducting layer. There is a direct relationship which shows that decreasing the sheet resistance of the coating decreases the emissivity of the surface [3]. Low emissivity can be achieved by coating glass with transparent conducting oxides such as SnO:F (a.k.a. FTO) or In_2O_3:SnO_2 (a.k.a. ITO), for example. However, a superior low-*E* coating is achieved by sandwiching an ultrathin layer of metal, typically silver, between two or more transparent, antireflecting thin film layers. Layer systems with two or even three silver layers have been designed and are widely used to not only block the near-room-temperature infrared radiation but also a good portion of the solar infrared, leading to products known as spectrally selective low-*E*, "double-silver", "triple-silver", or low-solar-gain low-*E* [4,5].

Low-*E* is a mature, "static" window technology that does not adapt to changing environmental conditions like the time of the day, weather conditions, or seasonal changes. Recently, dynamic, switchable windows emerged in the market [6]. The most developed and tested technology is based on electrochromic (EC) material systems. They have the ability to change transmittance and reflectance when a low voltage (typically 1.5–3 V) is applied across the transparent electrodes of the layer system (Fig. 1), thereby affecting its optical and energy performance.

To-date, the most durable and thus commercially viable EC material is tungsten oxide which can be switched by the intercalation of small ions such as hydrogen (protons), lithium or sodium ions, where lithium is preferred for performance and stability reasons [6,7]. One can control the transmittance of the visible and infrared radiation flowing in and out of the building by adjusting the small voltage applied across the multilayer system. The electrochromic properties of tungsten oxides have been extensively studied [6,8,9]. Practically all of the studies have been limited to the fully bleached and fully colored states. Very little has been reported on the intermediate states and in particular on the correlation between the intercalated ion density in the switching layers and their optical and thermal properties, which may be attributed to the difficulty of experimental studies.

An alternative approach to assess the optical and energy performance of EC windows is to adopt modeling tools, such as

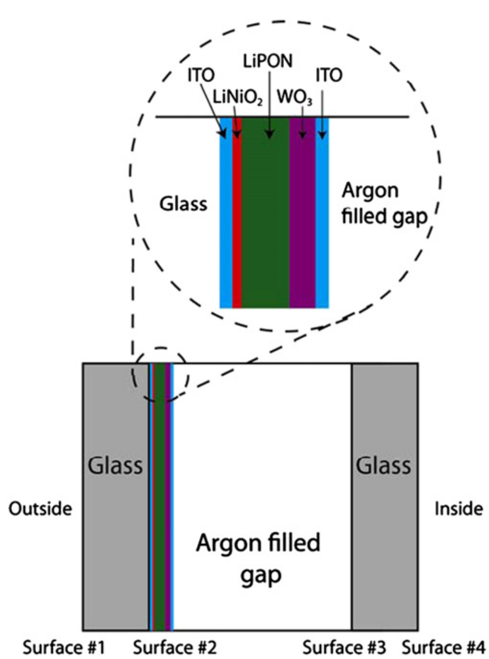

Fig. 1. Schematic of the electrochromic setup used in TFCalc and Window 6.3.26 simulations.

that demonstrated in recent publications by Nilsson and Roos [10], and Jonsson and Roos [11]. Nilsson et al. used WinSel, a window energy simulation tool developed at Uppsala University [12] to demonstrate how optical and thermal properties of windows (including coatings) can be used to evaluate the energy performance in a specific building under specific climate conditions. Also using WinSel, Jonsson studied different window glazing combinations with and without electrochromic coatings in their clear and tinted states [11].

In this paper, we demonstrate a similar methodology for modeling and assessing the optical and thermal performance of tungsten-oxide-based electrochromic windows including the intermediate states. Intermediate states are important as future EC windows are likely to offer not only fully bleached or fully tinted states as consumers may prefer partially tinted states for comfort reasons. We will discuss the coloration response for different thicknesses of the counter electrode (i.e. for different lithium ion reservoirs). We will compare optical properties and energy performance of EC windows in specific intermediate states with those of commercially available solar-control low-*E* windows. Finally, we will explore the energy performance of a hybrid window that is comprised of an EC-IGU and an additional low-*E* coating. Our modeling is designed to better utilize the advantages and potential offered by EC window technology.

2. Simulation

2.1. Approach

The simulation was performed in two stages. In the first stage, we used TFCalc 3.5.14 [13] to obtain the transmittance and reflectance from the front and back surfaces of glass coated with the layer system of interest as a function of wavelength. This was done by defining the multilayer thin film structure of an electrochromic device and using the refractive indices of the constituent layers. As shown in Fig. 1, the structure consisted of a glass pane with an indium tin oxide (ITO) bottom electrode (thickness 200 nm), a $LiNiO_2$ counter electrode (150 nm), a lithium phosphorus oxynitride (LiPON) ion conductor (1500 nm), the WO_3 electrochromic layer (483 nm) and finally an ITO top electrode (200 nm). LiPON is a solid electrolyte commonly used in thin film batteries and related technologies [14,15]. The justification for the thicknesses of the WO_3 and $LiNiO_2$ will be given in Section 2.2. In TFCalc, the illuminating source is the standard solar spectrum irradiance air mass 1.5 [16], and the incidence of light was normal to the surface of the glass.

The refractive indices of seven intermediate states for WO_3 and $LiNiO_2$ were taken from the publications by von Rottkay and Rubin [17,18], and the refractive indices of ITO from the Lawrence Berkeley National Lab website [19]. Since the refractive indices of LiPON were not available in the form of published data, a film of LiPON was deposited using RF sputtering at 13.56 MHz using a Li_3PO_4 target (99.99%) in nitrogen atmosphere. We measured the n&k components of the refractive index using a Woolam M2000 ellipsometer. For reasons of practicality we used the optical data determined for normal incidence light although it is understood that the angle of incidence of solar radiation changes with time of day and season.

In the second stage of simulation, the transmittances and reflectances of the seven intermediate states were used as input data for the Optics 5 and Window 6.3.26 [20] software packages. From Optics 5 we obtained the CIE color coordinates describing the window tint in transmission as seen from the inside. In Window 6.3.26, a dual-pane electrochromic insulated glass unit (IGU) was modeled in terms of U-value and SHGC. The IGU is assumed to consist of an electrochromic coated glass pane and a 3 mm thick second glass pane separated by