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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.

## I. 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  $\mu\text{m}$ ) radiation.

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  $\text{W}/(\text{m}^2 \text{K})$ . 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 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 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  $\text{In}_2\text{O}_3:\text{SnO}_2$  (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 (figure 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 solar 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 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.

## II. Simulation

### A. 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 figure 1, the structure consisted of a glass pane with an indium tin oxide (ITO) bottom electrode (thickness 200 nm), a  $\text{LiNiO}_2$  counter electrode (150 nm), a lithium phosphorus oxynitride (LiPON) ion conductor (1500 nm), the  $\text{WO}_3$  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  $\text{WO}_3$  and  $\text{LiNiO}_2$  will be given in section II B. 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  $\text{WO}_3$  and  $\text{LiNiO}_2$  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  $\text{Li}_3\text{PO}_4$  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 use 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 a 12.7 mm argon-filled gap as shown in figure 1. The EC coating stack was placed on surface 2 (by convention, surfaces are counted from the outside). Effects of the frame are neglected, i.e., we considered only the center-of-glass properties. Standard environmental conditions were used for the SHGC calculations as defined in standard NFRC 100-2010, which sets the inside temperature to 24°C and the outside air temperature to 32°C, with a wind speed of 2.8 m/s. The emissivity of the ITO layer was assumed to be 0.15, which is reasonable based on literature data [21-22].

### B. Charge and film thickness matching of the electrochromic layers

In this work we made the following assumptions:

1. In the fully bleached state, all mobile lithium ions are in the  $\text{LiNiO}_2$  layer. When the window is fully tinted, all Li ions are in the  $\text{WO}_3$  layer. Lithium in the LiPON is assumed to be constant and does not contribute to the switching state.
2. The total amount of mobile lithium will stay constant during the switching process. That is, mobile lithium ions will not undergo an irreversible chemical change or otherwise become immobile.

3. The window is large and the frame is well-insulating, thus the frame does not play an important role for the energy analysis. Therefore the simulation of thermal properties can be limited to the center-of-glass U-factor.

The switching state is determined by the localization of lithium within the layer stack. Changes of the mobile lithium ions localization within the stack can be expressed as volumetric charge density changes of lithium. The charge densities can be related to the film thicknesses of  $\text{WO}_3$  and  $\text{LiNiO}_2$  because the extinction coefficient for a given injected charge does not depend on thickness or mass density of the host layer but just on the injected lithium charge [17].

For  $\text{LiNiO}_2$  the volumetric charge density of lithium in its fully clear state is  $219 \text{ mC}/(\text{cm}^2 \mu\text{m})$  [18]. At a fixed thickness of 150 nm, we can calculate the lithium areal charge density to be  $32.85 \text{ mC}/\text{cm}^2$ . From the two assumptions above, we require that the same amount of charge to be present in  $\text{WO}_3$  when the system is in its fully tinted state. Knowing that the volumetric charge density for a fully tinted  $\text{WO}_3$  is  $68 \text{ mC}/(\text{cm}^2 \mu\text{m})$  [18], we calculate the appropriate thickness of  $\text{WO}_3$  to be 483 nm.

We have selected our intermediate states to be the same as the measured intermediate states for  $\text{LiNiO}_2$  given in [18]. The matching refractive indices  $n$  &  $k$  of  $\text{WO}_3$  are then interpolated from the data in [17] to ensure that the charge densities of the  $\text{WO}_3$  and  $\text{LiNiO}_2$  layers preserves the total lithium ion content. Table 1 shows a summary of the lithium charge matching of the intermediate states of the two host layers. As mentioned before, the lithium concentration in the LiPON ion conductor remains constant during the switching process and therefore does not need to be further considered.

### III. Results

#### A. Transmittance and solar heat gain coefficient

Figure 2 shows a plot of the solar transmittance as a function of wavelength of the intermediate states. In its fully clear state ( $0 \text{ mC}/\text{cm}^2$  in  $\text{WO}_3$ ), the average transmittance in the visible region is approximately 64%. The average visible transmittance is defined between 380 nm and 780 nm, and it is weighted to the photopic response of the human eye [23]. It is important to note that the transmittance decreases substantially with the first injection of lithium ions. For example, with a lithium ion density of only  $6.75 \text{ mC}/\text{cm}^2$  in  $\text{WO}_3$ , the maximum transmittance is already reduced to 25% in the visible region. Further intercalation of lithium into the  $\text{WO}_3$  layer results in further but less dramatic decrease of the transmittance. The noticeable fringes, which are very discernible in the infrared, arise from interference caused by reflection at the multiple interfaces within the thin film stack.

Figure 3 shows a plot of the SHGC and the solar and visible transmittances as a function of lithium concentration in the  $\text{WO}_3$  layer (bottom axis) and in the  $\text{LiNiO}_2$  layer (top axis). An important feature is that the changes in the transmittance and SHGC with the intercalation of lithium ions are nonlinear. Intercalating the electrochromic  $\text{WO}_3$  layer with  $6.75 \text{ mC}/\text{cm}^2$  of lithium ions resulted in more than 50% decrease in the SHGC. However, only a relatively small change in the SHGC is seen when the Li concentration is further increased from  $20.0 \text{ mC}/\text{cm}^2$  to  $32.9 \text{ mC}/\text{cm}^2$ . We include both visible ( $T_{\text{vis}}$ ) and solar ( $T_{\text{sol}}$ ) transmittance to account for both the visual appearance and the energy performance of the EC window. The standard solar spectra air-mass 1.5 was used to determine the solar transmittance in the wavelength range from 300 nm to 2500 nm [23]. Both  $T_{\text{vis}}$  and  $T_{\text{sol}}$  display the same nonlinear decrease as the amount of lithium increases in the  $\text{WO}_3$  layer.

## B. Coloration

Coordinates corresponding to the color space chromaticity diagram for both transmission and reflection for the intermediate states can be obtained from Optics 5 simulations. The color at various tinted states is an important factor in how EC windows are accepted by consumers. The appearance of the window from the outside is dictated by the color in reflection while the color of transmitted light is important to occupants inside the building. In Figure 4(a) we indicate how the coloration changes in both reflection (R) and transmission (T) as the window darkens. In the clear state, the color is relatively neutral. It shifts towards blue as the window is tinted, which is typical for tungsten-oxide-based EC systems.

We explored the idea of maintaining a more neutral coloration in the tinted state by increasing the thickness of the LiNiO<sub>2</sub> layer. The amount of mobile lithium is kept constant at 32.84 mC/cm<sup>2</sup>, which was the value previously considered for fully charged WO<sub>3</sub> of thickness of 483 nm. When a thicker LiNiO<sub>2</sub> is selected, it is still charged to its maximum volumetric charge of  $Q_{full} = 219 \text{ mC}/(\text{cm}^2 \mu\text{m})$  in its clear state, but the Li is not fully unloaded in its tinted state. A color shift towards a more neutral state is therefore obtained at the expense of a reduction of the maximum transmittance in the clear state. Using again the data for partially lithiated nickel oxide [18] we can determine the layer thickness necessary to maintain the same amount of lithium in LiNiO<sub>2</sub> using a simple proportional ratio:

$$S_{thick} = S_{full} \frac{Q_{full}}{Q_{full} - Q_{ext}} \quad (1)$$

where  $Q_{ext}$  is the lithium charge that has been extracted from a fully charged LiNiO<sub>2</sub> to obtain the volumetric charge density of the partially charged LiNiO<sub>2</sub> of interest. The result is shown in Table 2. Figure 4b shows the change in coloration when the thickness of LiNiO<sub>2</sub> is increased while a constant thickness of WO<sub>3</sub> is maintained. The coloration in both reflection and transmission tends to be more neutral with thicker LiNiO<sub>2</sub>, i.e. away from the previously observed blue shift, however, we stress that this advantage is obtained at the expense of a reduction of the maximum transmittance in the clear state.

## C. Comparison with conventional low-E coatings

We compare the results of the simulated electrochromic window with two examples of spectrally selective silver-based low-E windows which are readily commercially available. The first example is the LoE<sup>2</sup> 272 manufactured by Cardinal Glass Industries, and the second ClimaGuard 63/31 LE from Guardian. Both these windows use 3 mm glass and the coating is on surface #2. The emissivities for the two example windows are 0.042 (LoE<sup>2</sup> 272) and 0.026 (ClimaGuard 63/31 LE). Further specifications for these windows can be found in the database "Library of Glass" found in the LBNL Window software [20]. In each case, the low-E coating was placed on surface #2 of the IGU since this has the greatest energy benefit. The simulation parameters such as environmental conditions were kept the same to ensure that a comparison is valid. The results are shown in Table 3. The silver-based low-E window #1 has the highest transmittance and both low-E windows show a lower U-value compared to the EC windows. The low-E windows have a lower SHGC when compared to the clear state of the EC window. However, as the EC window darkens, its SHGC decreases and can become lower than the SHGCs of the low-E windows. In Table 3, we also show the light-to-solar gain ratio (LSG). The higher the ratio, the greater the spectral selectivity, a characteristic desired for glazing systems in hot climate conditions. For

the EC system, the LSG ratio is high in its clear state, and drops rapidly as the windows darkens. Both low-E systems show a high LSG ratio indicating that they are well suited for hot climate locations.

#### **D. Considerations for an EC/low-E hybrid window**

The EC layer stack intrinsically has low-E properties due to the conducting transparent oxide electrode on top of the layer stack. However, one may consider the benefits of having an additional, silver-based low-E coating on surface #3 of the IGU. We call this an EC/low-E hybrid window. We thus should compare an EC window (with its intrinsic low-E property), with a traditional silver-based low-E window, and an EC/low-E hybrid window. In the simulation, the Cardinal Glass - LoE<sup>2</sup> 272 was used as the low-E window.

The results from the previous section show that there are advantages of having traditional silver-based low-E windows due to the achievable very low U-value. However, when the EC window is darkened, it can achieve a very low SHGC, which is advantageous under sunny conditions.

To evaluate the potential benefit of an additional low-E coating on surface 3, one needs to define environmental conditions of interest. For this, we have used the NFRC 100-2010 environmental conditions as specified in the software, and the temperature of the glass surfaces based on the defined indoor and outdoor temperatures for summer and winter seasons. The two surfaces of each glass pane have practically the same temperature due to the relatively high heat conductivity of glass, i.e., it is sufficient to only show the temperature of one surface for each pane. In figure 5, the temperatures of the two glass panes for the EC/low-E hybrid window are depicted with squares (□, ■). This is compared with the temperatures of the glass panes to the conventional EC windows depicted with circles (○, ●), with the EC layer stack placed on surface #2.

In figure 5a, when the EC coating is on surface #2 and the low-E coating is on surface #3, the temperature of the outer pane increases when the EC layer stack darkens and increasingly absorbs solar radiation. The temperature on surface #1 in the hybrid window (□) is comparable to the case of a traditional EC window with the EC stack on surface #2 (○). The temperature of surface #3 is approximately 32°C independent of the tinting state for the case of the hybrid window (■). The traditional EC configuration assumes a surface #3 temperature of approximately 34°C (●), which is slightly higher than the comparable temperature for the hybrid EC/low-E window.

For the sake of comparison, and not necessarily for practical use, we include the case when the order of the low-E and EC layers in a hybrid EC/low-E window is reversed, i.e. when the low-E and EC coatings are applied on surfaces #2 and #3, respectively. Figure 5b shows the temperatures of surface #1 and surface #3 in this configuration. The temperature of surface #3 is increasing with the tint of the EC layer due to absorption of solar radiation. In its darkest state, the temperature of the inner pane of the IGU is substantially higher than the temperature of surface #1 (outer pane). This case is usually not desirable since it would lead to much increased cooling loads in warm climates.

#### **IV. Discussion**

The visible transmittance for a low-E coating is generally higher than the transmittance of an electrochromic window in its clear state. In low-E windows, ultrathin silver is used, since silver exhibits



the lowest absorption of visible light of all metals while having very good conductivity, hence low emissivity. The reflection in the visible, usually associated with metals, is suppressed by the use of anti-reflecting layers. The EC layer stack, in contrast, is comprised of relatively thick, slightly absorbing oxide and oxynitride layers. The total layer stack in our example is quite thick, leading to relatively low transmittance even in the clear state. The total thickness of the device can be reduced substantially, as 1% transmission in the dark state may be lower than needed. A few percent higher transmittance in the dark state would allow for a thinner device, and hence also higher transmittance in the clear state without compromising the SHGC. For commercial building applications, a lower limit of visual transmittance of about 60% in the clear state is considered acceptable, although some enhancements are possible by implementing antireflection coatings to EC windows [24]. Attention is often put on the lower bound of transmittance since it determines the lower limit of the SHGC and the suppression of glare, which, when insufficiently addressed, requires the presence of curtains, blinds or other kinds of shading devices. In intermediate states, as they may be desired by consumers, glare is suppressed but building occupants may still desire to use additional shading options.

The results show that even a slight coloration of the EC window reduces the SHGC compared to the two commercial low-E windows. Such reduction can be quite desirable from an energy performance point of view.

The U-factor includes heat transfer by conduction, convection, and thermal radiation (but excludes solar radiation, as mentioned in the Introduction), and is defined as

$$U = \frac{Q_A}{\Delta T} \quad (2)$$

where  $Q_A$  is the thermal energy transfer per unit area and time, and  $\Delta T$  is the difference in temperature between the outside and inside. The software Window 6.3.26 deals with radiated heat transfer using the Stefan-Boltzmann law for the case of a grey body radiation:

$$Q_A = \varepsilon \sigma T^4 \quad (3)$$

where  $\varepsilon$  is the emissivity,  $\sigma$  is the Stefan Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ) and  $T$  is the absolute temperature in Kelvin. This equation is used for each surface with its own temperature and emissivity. Since the emissivity of a silver-based coating is smaller than the emissivity of a transparent conducting oxide, it is clear that the intrinsic low-E property of a traditional EC stack is unaffected by the switching and will not be as good as the silver-based low-E coating. The simulation shows that the additional benefit of a silver-based low-E coating on surface 3 affects the temperature of the inner glass pane only marginally, and therefore the cost for such additional low-E coating may not be economically justified.

The idea of adding a low-E coating to a conventional EC window was recently discussed by Jonsson and Roos [11] who investigated the energy balance using EC window with different types of low-E coatings (silver based, transparent conducting oxide, and solar selective). Here we extend the study of the hybrid system and consider the differences in the energy performance when we reverse the order of the two coatings that are applied. Due to the absorbing nature of EC in its tinted state, there is a great difference in performance as to on which surfaces the low-E and EC stack should be placed.

Figure 5a shows that when placing the EC on surface #2, a significant amount of heat is absorbed on the outer pane causing the increase in its temperature while the inner pane remains relatively cool. This configuration allows the low-E coating on surface #3 to reflect the absorbed heat (coming from the EC when tinted). The situation is very different when the low-E coating is placed on surface #2 and the EC is

on surface #3 (figure 5b). In this configuration, although the temperature of the outer glass pane is substantially lower compare to the previous configuration, the inner pane is excessively heated in its tinted state as the EC absorbs solar radiation. In the summer when the building is typically cooled, this extra heat load would require addition cooling, i.e. such window would have a very negative effect on energy efficiency.

Figure 6 shows the SHGC of a single EC on surface #2 and both configurations of the hybrid window as a function of the Li concentration in  $WO_3$ . Clearly, in the EC/low-E hybrid system, with the EC is on surface #3 and low-E on #2, the SHGC is higher and actually makes cooling requirement much worse compared to the single EC placed on surface #2. There is a small beneficial reduction of the SHGC when using a hybrid window (EC on surface #2; low-E on surface #3). The slight decrease in the SHGC may not be worthwhile the cost of the additional layer. In the unusual case where the low-E is placed on surface #2 and the EC layer system is on surface #3, the SHGC is much higher, which is under most circumstances undesirable.

## V. Conclusions

In this contribution, we used published optical data and software tools to assess the optical and energy performances of the intermediate states of a tungsten-oxide based electrochromic window. The results show that even with a small amount of coloration by lithium intercalation in  $WO_3$ , there is a substantial change in the energy performance due to a significant decrease in the SHGC. We also investigated the possibility of a hybrid window by placing EC and low-E coatings on different surfaces. Our result shows that there is little to additional benefit for a configuration where the EC layer stack on surface #2 is complemented with a low-E coating on surface #3. Reversing the order of EC and low-E coatings implies raising the SHGC to undesirably high levels.

## References

- [1] United Nations Environmental Programme - Annual Report, 2010, <http://www.unep.org/annualreport/2010/>.
- [2] J. Carmody, S. Selkowitz, D. Arasteh, L. Hescong, Residential Windows: A Guide to New Technologies and Energy Performance, 2nd ed., W.W Norton, 2000.
- [3] H.J. Gläser, Large Area Glass Coating, Von Ardenne Anlagentechnik, Dresden, 2000.
- [4] A. Laouadi, M.R. Atif, A. Galasiu, Towards developing skylight design tools for thermal and energy performance of atriums in cold climates, *Build. Environ.*, 37 (2002) 1289-1316.
- [5] C. Schaefer, G. Brauer, J. Szczyrbowski, Low emissivity coatings on architectural glass, *Surf. Coat. Technol.*, 93 (1997) 37-45.
- [6] C.G. Granqvist, Handbook of Inorganic Electrochromic Materials, Elsevier, Amsterdam, 1995.
- [7] C.-G. Granqvist, Electrochromic materials: Out of a niche, *Nature Material*, 5 (2006) 89-90.
- [8] C.G. Granqvist, Transparent conductors as solar energy materials: A panoramic review, *Sol. Energy Mater. Solar Cells*, 91 (2007) 1529-1598.
- [9] P.M.S. Monk, R.J. Mortimer, D.R. Rosseinsky, *Electrochromism and Electrochromic Devices*, Cambridge University Press, New York, 2007.
- [10] A.M. Nilsson, A. Roos, Evaluation of optical and thermal properties of coatings for energy efficient windows, *Thin Solid Films*, 517 (2009) 3173-3177.

- [11] A. Jonsson, A. Roos, Evaluation of control strategies for different smart window combinations using computer simulations, *Solar Energy*, 84 (2010) 1-9.
- [12] WinSel, <http://hem.bredband.net/amor/winsel.htm>
- [13] TFCalc, 3.5.14, Software Spectra, Inc, <<http://www.sspectra.com/>>
- [14] J.B. Bates, N.J. Dudney, G.R. Gruzalski, R.A. Zuhr, A. Choudhury, C.F. Luck, J.D. Robertson, Electrical properties of amorphous lithium electrolyte thin films, *Solid State Ionics*, 53 (1992) 647-654.
- [15] J.B. Bates, N.J. Dudney, B. Neudecker, A. Ueda, C.D. Evans, Thin-film lithium and lithium-ion batteries, *Solid State Ionics*, 135 (2000) 33-45.
- [16] Reference Solar Spectral Irradiance: Air Mass 1.5, <http://rredc.nrel.gov/solar/spectra/am1.5/>
- [17] K. von Rottkay, M. Rubin, S.J. Wen, Optical indices of electrochromic tungsten oxide, *Thin Solid Films*, 306 (1997) 10-16.
- [18] M. Rubin, K. von Rottkay, S.J. Wen, N. Özer, J. Slack, Optical indices of lithiated electrochromic oxides, *Sol. Energy Mater. Solar Cells*, 54 (1998) 49-57.
- [19] Lawrence Berkeley National Laboratory, <http://windows.lbl.gov/materials/chromogenics/N&K-coverpage.html>
- [20] Window, <http://windows.lbl.gov/software/window/window.html>
- [21] K. Sun, W. Zhou, X. Tang, Z. Huang, F. Lou, D. Zhu, Effect of the heat treatment on the infrared emissivity of indium tin oxide (ITO) films, *Appl. Surf. Sci.*, 257 (2011) 9639-9642.
- [22] H.M. Ali, H.A. Mohamed, S.H. Mohamed, Enhancement of the optical and electrical properties of ITO thin films deposited by electron beam evaporation technique, *Eur. Phys. J.-Appl. Phys*, 31 (2005) 87-93.
- [23] E. Finlayson, D. Arasteh, H. C, M. Rubin, M.S. Reilly, WINDOW 4.0: Documentation of Calculation Procedures, Lawrence Berkeley Laboratory, University of California, 1993; <http://gaia.lbl.gov/btech/papers/33943.pdf>
- [24] A. Jonsson, A. Roos, Visual and energy performance of switchable windows with antireflection coatings, *Solar Energy*, 84 (2010) 1370-1375.

Table 1

A summary of the Li charge density matching of the intermediate states of the electrochromic and counter electrode layers.

State	LiNiO <sub>2</sub>		WO <sub>3</sub>	
	Li volumetric charge density (mC/(cm <sup>2</sup> μm))	Li areal charge density for 150 nm thick film (mC/cm <sup>2</sup> )	Li volumetric charge density (mC/(cm <sup>2</sup> μm))	Li areal charge density for 483 nm thick film (mC/cm <sup>2</sup> )
Clear	219	32.9	0	0
	174	26.1	14	6.75
	120	18	31	14.85
	85.2	12.8	42	20.07
	64.6	9.7	48	23.16
	52.2	7.8	52	25.02
Dark	0	0	68	32.85

Table 2: Variation of the thickness in LiNiO<sub>2</sub> to ensure that an areal lithium charge density of 32.84 mC/cm<sup>2</sup> is maintained.

LiNiO <sub>2</sub>	
Li volumetric charge density (mC/(cm <sup>2</sup> μm))	Thickness to accommodate the charge (nm)
220	150
167	197
154	213
134	245
100	332
45	730

Table 3

Table 3 Comparison of the optical and energy performances of the electrochromic window at various states and two commercially available silver-based low-E windows. EC refers to electrochromic and the value inside the parentheses refers to the Li volumetric charge density in WO<sub>3</sub>.

Window	T <sub>vis</sub> (%)	T <sub>sol</sub> (%)	SHGC	U-factor (W/m <sup>2</sup> K)	LSG (T <sub>vis</sub> /SHGC)
EC (0)	64	36	0.43	1.62	1.49
EC (14)	25	12.7	0.20	1.62	1.25
EC (31)	8	4.5	0.12	1.62	0.67
EC (42)	5	2.3	0.10	1.62	0.50
EC (48)	3	1.3	0.09	1.62	0.33
EC (52)	2	1	0.09	1.62	0.22
EC (68)	1	0.5	0.08	1.62	0.13
Cardinal Glass Industries - LoE <sup>2</sup> 272	72	37.7	0.41	1.39	1.76
Guardian - ClimaGuard 63/31 LE	63	28.3	0.31	1.35	2.03

## Figure Captions

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

Figure 2: A plot of the visible transmittance as a function of wavelength for the intermediate states.

Figure 3: A plot of the SHGC and both the solar and visible transmittance as a function of the Li concentration in the  $\text{WO}_3$  layer (bottom axis) and the  $\text{LiNiO}_2$  layer (top axis). The solid lines are for visual aid purpose.

Figure 4: (a) The change in the coloration of the electrochromic window tints in both transmission (T) and reflection (R). In its clear state, the window remains color-neutral. It shifts towards blue as it darkens. (b) Adjusting the thickness of the  $\text{LiNiO}_2$ , the blue coloration in the tinted state can be shifted to a more neutral color.

Figure 5: (a) The temperature of the inner ( $\square$ ) and outer ( $\blacksquare$ ) glass pane for a hybrid window where the EC is on surface #2 and low-E on surface #3. This is compared to a conventional EC windows where the EC layer is placed on surface #2 ( $\circ, \bullet$ ); (b) The temperature of the inner ( $\square$ ) and outer ( $\blacksquare$ ) glass pane for a hybrid window with low-E on surface #2 and EC on surface #3. This is compared to a conventional EC window where the EC layer is placed on surface #2 ( $\circ, \bullet$ ).

Figure 6: A comparison of the SHGC for an IGU with an EC layer stack on surface #2 ( $\blacksquare$ ), and the two hybrid window configurations of Figures 5(a) ( $\blacktriangle$ ) and 5(b) ( $\bullet$ ).

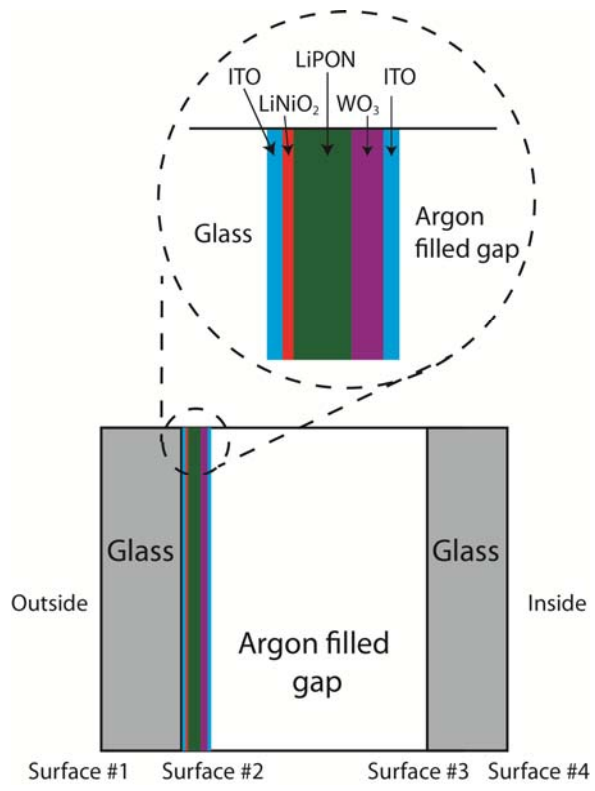


Figure 1



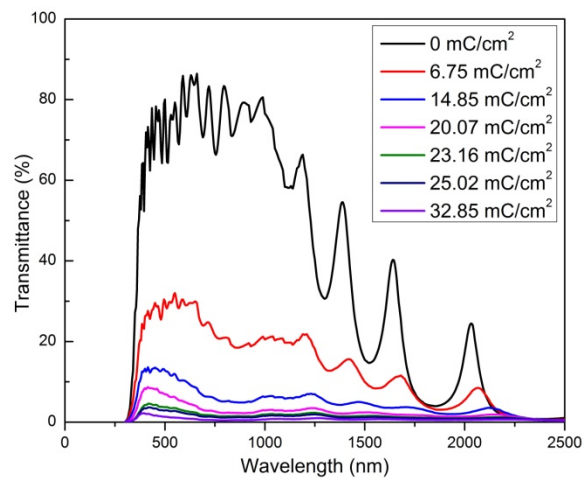


Figure 2

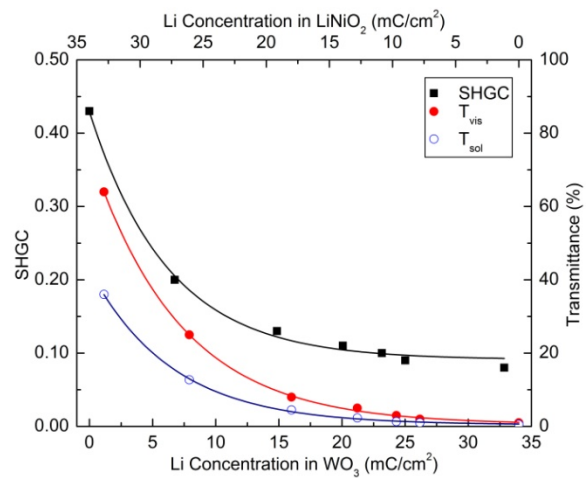


Figure 3

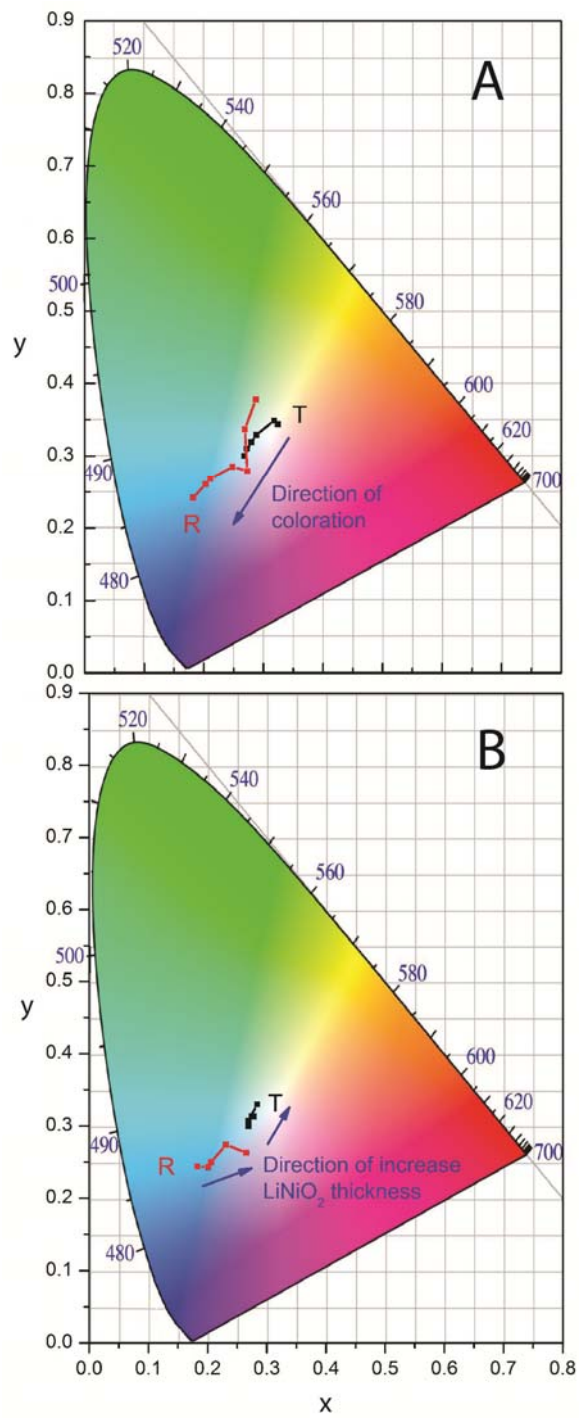


Figure 4

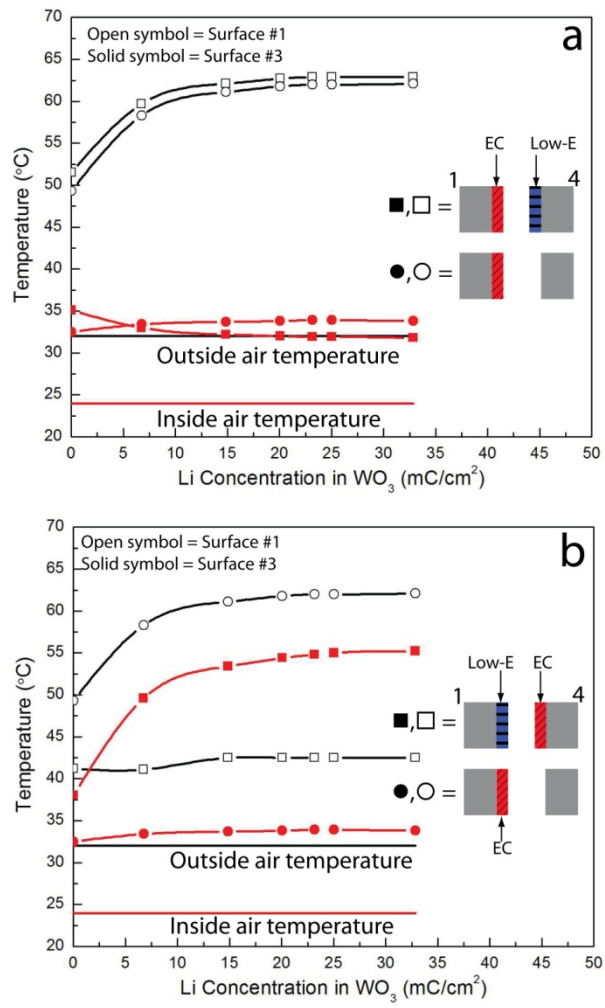


Figure 5.

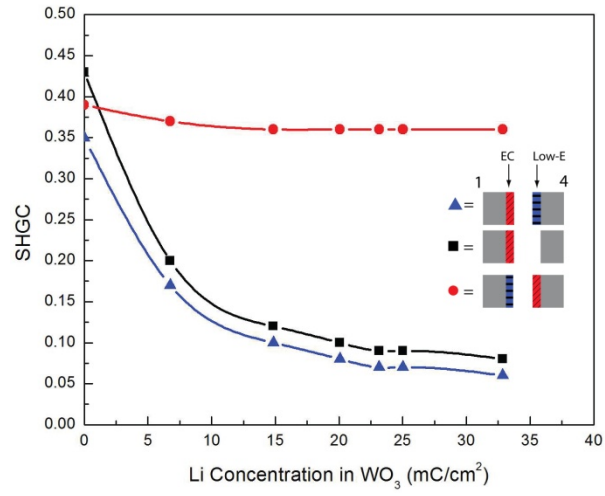


Figure 6