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Examination of the technical potential of near-infrared switching thermochromic windows for commercial building applications

Sabine Hoffmann, Eleanor S. Lee*, César Clavero

Building Technology and Urban Systems Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Mailstop 90-3111, 1 Cyclotron Road, Berkeley, CA 94720, USA

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ABSTRACT

Current thermochromic windows modulate solar transmission primarily within the visible range, resulting in reduced space-conditioning energy use but also reduced daylight, thereby increasing lighting energy use compared to conventional static, near-infrared selective, low-emittance windows. To better understand the energy savings potential of improved thermochromic devices, a hypothetical near-infrared switching thermochromic glazing was defined based on guidelines provided by the material science community. EnergyPlus simulations were conducted on a prototypical large office building and a detailed analysis was performed showing the progression from switching characteristics to net window heat flow and perimeter zone loads and then to perimeter zone heating, ventilation, and air-conditioning (HVAC) and lighting energy use for a mixed hot/cold climate and a hot, humid climate in the US. When a relatively high daylight transmission is maintained when switched (Tsol = 0.10–0.50 and Tvis = 0.30–0.60) and if coupled with a low-e inboard glazing layer (e = 0.04), the hypothetical thermochromic window with a low critical switching temperature range (14–20 °C) achieved reductions in total site annual energy use of 14.0–21.1 kW h/m^2-floor-yr or 12–14%[1] for moderate- to large-area windows (WWR ≥ 0.30) in Chicago and 9.8–18.6 kW h/m^2-floor-yr or 10–17%[2] for WWR ≥ 0.45 in Houston compared to an unshaded spectrally-selective, low-e window (window E1) in south-, east-, and west-facing perimeter zones. If this hypothetical thermochromic window can be offered at costs that are competitive to conventional low-e windows and meet esthetic requirements defined by the building industry and end users, then the technology is likely to be a viable energy-efficiency option for internal load dominated commercial buildings.

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1. Introduction

Thermochromic (TC) windows consist of a thin polymer film or inorganic coating on glass that passively switches in response to variable thermal conditions. The thermochromic is typically applied to the outer glass layer of an insulating glass unit and when it reaches a certain critical temperature (or range of temperatures) due to high incident solar radiation and/or high outdoor temperatures, the thermochromic changes or switches from a clear to a tinted transparent state, reducing the solar and visible transmittance of the window. The process of switching from the clear to tinted state is reversible and for some thermochromic materials, hysteresis can be observed (i.e., switching from tinted to clear occurs at a lower temperature than switching from clear to tinted) [1–3]. As a passive system, thermochromic performance is highly dependent on the interaction between the material and the climatic conditions to which it is subjected. The current understanding is that if the material properties of the thermochromic can be properly tuned, then the technology has the potential to significantly improve building energy efficiency.

A wide variety of materials have been found to have thermochromic properties, including polymers, organic and inorganic compounds [4]. Most of them offer good modulation of the visible transmission. However, they generally do not offer proper switching in the near-infrared (IR) portion of the solar spectrum. Several transition metal oxides and related compounds such as Fe_3O_4, $FeSi_2$, NbO_2, NiS, Ti_2O_3, Ti_4O_7, Ti_5O_9, V_2O_3, and VO_2 offer interesting thermochromic properties. Among them, vanadium dioxide (VO_2) is the only metal oxide that exhibits a sharp thermochromic transition close to room temperature (68 °C). The switching takes place due to a semiconductor to metal (MIT) transition that is accompanied by a first order structural phase transition from

* Corresponding author. Tel.: +1 510 486 4997.
E-mail address: eslee@lbl.gov (E.S. Lee).

[1] Percentage values refer to the site annual energy use for the perimeter zone of a specific orientation; the highest relative savings were usually reached for south or west orientation.

[2] See above.

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monoclinic to rutile. As a consequence, a drop in the resistance of around four orders of magnitude is observed [5], along with a remarkable decrease of the IR transmittance [6]. The origin of the MIT transition still remains controversial. It is unclear whether the insulating behavior in the low temperature phase is due to a Peierls distortion inducing the insulator energy gap, or to a Mott transition due to electron localization and increase in electron–electron repulsion [7–9]. Typical values for the modulation of solar transmission (ΔTsol) are not usually larger than 0.1 for VO_2 thin films, while visible transmittances (Tvis) do not exceed 0.4 [10].

The material science community has defined performance objectives to guide development of the next generation of thermochromic materials, namely: (a) lower the critical temperature at which the TC material switches to the tinted state from 68 °C to 25 °C for VO_2-based materials, (b) broaden the modulation of solar transmission (ΔTsol), and (c) achieve a high visible transmittance (Tvis) in the unswitched state [10]. Several solutions have been proposed to overcome these difficulties. The critical temperature can be widely tuned by doping VO_2 with different transition metals [10–12], giving rise to significant changes in the electronic structure and thus the thermochromic transition. For example, VO_2 doping with W leads to a drop of the transition temperature at a rate between 5 and 24 K/at% W, depending on the deposition conditions [10,13]. Tvis can be enhanced by the addition of W, but the effect is not large [14]. Li et al. [15,16] proposed the use of VO_2 nanoparticles embedded in a dielectric host to increase ΔTsol. When in their metallic phase, the VO_2 nanoparticles undergo localized surface plasmon resonance (LSPR), leading to an increased absorption in the visible and near-IR ranges. Values of ΔTsol around 0.167 and Tvis as high as 0.72 and 0.62 in the semiconducting and metallic states respectively can be achieved. Furthermore, the use of core–shell nanostructures, where VO_2 comprises the shell, will allow reaching ΔTsol values in excess of 0.20 at the expense of a lower Tvis around 0.59 in the semiconducting state [15]. Also, tuning of the transition temperature and Tvis can be easily achieved by doping VO_2 with different transition metals. Due to its particular electronic structure, VO_2 exhibits a *2p–3d* interband transition around the visible range, leading to strong optical absorption and thus low Tvis values. Doping with Mg broadens the bandgap of VO_2 leading to an increase in Tvis to around 0.5 [17].

Following the work of previous studies that have used building energy simulations to assess the potential energy efficiency benefits of thermochromic windows within simple room models [18,19], this study quantifies the benefits associated with thermochromic windows that meet the above stated performance objectives in order to provide developers with a deeper understanding of the level of impact associated with advancements in material science. The relationships between window heat gain, perimeter zone loads, and heating, cooling, and lighting energy use are complex and non-trivial. Performance is dependent on climate, building type (as defined by construction and internal load profile), window orientation, window size, and the efficiencies of the space conditioning and lighting equipment.

A hypothetical, near-infrared selective thermochromic window is modeled (Tsol=0.50–0.10 and Tvis=0.6–0.3) with different ranges of switching temperature. While the properties of these emerging thermochromic coatings have shown great improvement in the last few years, we note that significant research needs to be carried out in order to achieve these optimum thermochromic characteristics. Design of coatings consisting of nanostructured dielectric materials and doped VO_2 will help to optimize the thermochromic properties of these systems.

The EnergyPlus building energy simulation tool is used to determine the incremental differences in energy performance for perimeter zones in a typical large commercial office building. Performance is evaluated for a mixed cold/hot northern climate and a hot, humid southern climate in order to identify regions in the United States where thermochromic windows are most likely to provide significant energy savings compared to static, near-infrared selective, low-emittance windows which are currently the leading-edge, commercially-available technology of today.

2. Methods

2.1. Properties of the thermochromic windows

2.1.1. Transmittance in visible and solar spectrum of the thermochromic glazing layer

In order to regulate solar transmission without negatively reducing daylight, thermochromic switching from the clear to tinted state should occur primarily in the near-infrared (NIR) spectrum (780–2500 nm). Since about half of the solar energy is emitted in the visible spectrum (380–780 nm), there is a physical limit to the ratio of visible to solar transmittance over the full solar spectrum (300–2500 nm). The best spectrally-selective glazings have a maximum luminous efficacy, Ke, or ratio of visible transmittance (Tvis) to solar heat gain coefficient (SHGC) of about 2.5.

For this study, we defined a hypothetical spectral distribution for the TC glazing layer where the transmittance of shorter wavelengths in the visible spectrum is maintained at a high level when the glazing is fully tinted while wavelengths in the near-infrared spectrum were cut down to a transmittance of 0.05 in the fully tinted state in order to minimize the overall solar transmittance. This hypothetical value of near-infrared transmittance represents a target value when the spectral transmittance of a real material over the NIR spectrum is integrated. The spectral distribution was optimized for luminous efficacy based on the CIE Standard Illuminant D65 [20] and the CIE 1931 standard observer [21] (Y component) for visible transmittance, and on global radiation data from ISO 9845 [22] for solar transmittance. A value of Tvis=0.30 and Tsol=0.10 for the TC glazing layer in the fully tinted state leads to a luminous efficacy of Ke=2.25 for the TC glazing system (Table 1). Color neutrality and appearance were not part of the optimization. Two intermediate states were defined by interpolation between the clear and tinted states; the spectral distributions for all four states are given in Fig. 1.

Table 1
Spectrally averaged properties of the glazing layers and thermochromic insulating glass unit as used in the simulation model.

	Layer 1 (outdoor) TC		Gap	Layer 2 clear low-e	Insulating glazing unit	
	Clear	Tinted			Clear	Tinted
Thickness [mm]	6		16	6	28	
Solar transmittance	0.5	0.1		0.77	0.39	0.08
Solar front reflectance	0.35	0.45		0.07	0.37	0.45
Solar back reflectance	0.35	0.45		0.07	0.37	0.45
Solar absorptance	0.15	0.45		0.16		
Visible transmittance	0.6	0.3		0.88	0.53	0.27
Front side emissivity	0.84	0.84		0.04		
Back side emissivity	0.84	0.84		0.84		
U-value (W/m^2 K)					1.45	1.45
SHGC					0.47	0.12
Ke (=Tvis/SHGC)					1.13	2.25

Note: Solar-optical properties based on CIE Illuminant D65 (ISO/CIE 10526 Table 1), CIE 1931 standard observer Y, ISO 9845 Table 1, column 5, the *U*-value and SHGC from EnergyPlus. Gas fill was 90% argon and 10% air. SHGC: solar heat gain coefficient and Tvis: visible transmittance.