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Electrochromic foil-based devices: Optical transmittance and modulation range, effect of ultraviolet irradiation, and quality assessment by 1/*f* current noise

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Abstract

We introduce electrochromic (EC) technology for modulating the transmittance of visible light and solar radiation in window apertures, with focus on recent work on foil-type devices embodying sputter deposited WO_3 and NiO films joined by a polymer electrolyte. The purpose of this paper is to present a number of new and preliminary results showing that (*i*) double-sided antireflection coatings based on dip coating can enhance the transmittance significantly, (*ii*) tandem foils can yield a ratio between bleached-state and colored-state transmittance exceeding fifty, (*iii*) solar irradiance onto the EC device can enhance its charge insertion dynamics and thereby its optical modulation, and (*iv*) electromagnetic noise spectroscopy may serve as quality assessment of EC devices.

Keywords: Electrochromism; Smart window; Thin film; Optical properties; Tungsten oxide; Nickel oxide; Sputtering; Noise spectroscopy

1. Introduction

Global warming is no longer in need of an introduction, and means to alleviate its effects are of the greatest urgency. The effects are not just hypothetical or lying in the distant future; for example, it has been stated that the warming and precipitation trends due to antropogenic climate change during the past 30 years already claim over 150,000 human lives each year [1,2]. These changes are also expected to be accompanied by more common and/or extreme events such as heat-waves, heavy rainfall, and storms and coastal flooding. It is also possible that non-linear climate responses will lead to 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]. Major changes in energy technology are necessary, and, furthermore, they must account 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].

To combat global warming, it is obvious that one should focus on the built environment; considering the case of the EU (15), about 40% of the total energy is currently used for heating, cooling, lighting, and ventilation [6]. Not surprisingly, the European Commission, in its "Action Plan for Energy Efficiency" of 20 October 2006, 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…".

The energy demand for air conditioning has grown very rapidly—by about 17% per year—in the EU [7], and already

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today electrically driven air conditioning dominates the peak power during the summer in parts of Europe. Similar results pertain to the US.

The increase in the energy expenditure on air conditioning is based on a increasing demand for 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 façades. Large glazed areas tend to give cooling requirements, at least in commercial buildings, but small windows give bad indoor comfort and hence poor job satisfaction with ensuing poor job performance. One way to improve the situation is to have building envelopes 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, which then opens new possibilities to obtain energy efficient day-lighting.

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 recent work for the California Energy Commission [8,9]. The summary of this report states that [8]:

> "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 detailed numbers on the energy savings, given above, are likely to be underestimated rather than overestimated and account neither for novel transparency control strategies based on physical presence [10] nor for novel day-lighting strategies based on "light balancing" [11].

The purpose of this paper is to outline some recent work on the science and technology of electrochromic (EC) foils [12], which is presently advancing rapidly and holds prospects for low-cost "smart windows" combining energy efficiency and indoor comfort in new as well as existing buildings. Specifically, this paper considers four novel features: (*i*) transmittance increase by antireflection coating, (*ii*) achievable optical modulation range, (*iii*) effects of ultraviolet irradiation on EC performance, and (*iv*) possibilities to use electromagnetic noise spectroscopy for quality assessment of EC devices [13]. The intention is to present preliminary data from ongoing work rather than to provide full-length, detailed accounts.

2. Overview over electrochromic materials and device design

An EC device resembles a thin film electrical battery, as evident from Fig. 1. The device has five superimposed layers on a transparent substrate, typically of glass or flexible polyester (PET) foil, or positioned between two such substrates in a laminate arrangement [14]. The outermost layers are transparent electrical conductors, typically of In_2O_3:Sn (*i.e.*, indium tin oxide, ITO) [15]. One of these layers is coated with an EC film, and the other is coated with an ion storage film, with or without EC properties. The two films must comprise nanomaterials with well specified nanoporosities (analogously with the case of battery electrodes). A transparent ion conductor (electrolyte) is at the middle of the device and joins the EC and ion storage films. A voltage applied between the transparent electrodes leads to charge being shuttled between the EC and ion storage films, and the overall transparency T is then changed. A voltage pulse with opposite polarity—or, with suitable materials, short circuiting—makes the device regain its original properties. The optical modulation requires a DC voltage of 1 to 2 V. The charge insertion into the EC film(s) is balanced by electron inflow from the transparent electrode(s); these electrons can produce intervalency transitions, which is the basic reason for the optical absorption.

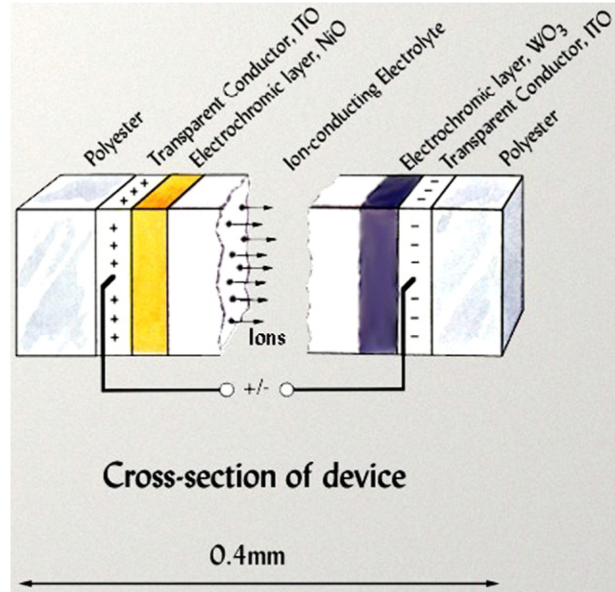

Fig. 1. Sketch of an EC foil-type device.

Regarding materials in EC devices, the ITO can be replaced by ZnO:Al, SnO_2:F, or similar oxides (or, possibly, carbon nanotubes) if the availability and cost of indium turn out to be problematical [16,17]. In fact, the global availability of indium does not seem to be fully clear today (2007), and on one hand it has been stated that it is ample and about as large as that of silver [18], but it has also been claimed that the availability is much too low to allow widespread deployment of indium-containing thin film solar cells [19]. The EC film is WO_3-based in almost all devices for window applications, whereas there are many possibilities for the counter electrode [12,14,20,21]. Among the latter, films based on IrO_2 and NiO have enjoyed much interest recently. IrO_2-based alternatives are inherently expensive, but good EC properties are maintained after dilution with cheaper Ta_2O_5 [22]. NiO-based films combine moderate cost with excellent optical properties; the transmittance can be boosted if