



Critical review

Electrochromics for smart windows: Oxide-based thin films and devices



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ABSTRACT

Electrochromic (EC) smart windows are able to vary their throughput of visible light and solar energy by the application of an electrical voltage and are able to provide energy efficiency and indoor comfort in buildings. [Section 1](#) explains why this technology is important and timely by first outlining today's precarious situation concerning increasing energy use and associated effects on the world's climate, and this section also underscores the great importance of enhancing the energy efficiency of buildings by letting them function more in harmony with the environment—particularly its varying temperature—than is possible with current mainstream technologies. This same chapter also surveys recent work on the energy savings and other benefits that are possible with EC-based technologies. [Section 2](#) then provides some notes on the history of the EC effect and its applications. [Section 3](#) presents a generic design for the oxide-based EC devices that are most in focus for present-day applications and research. This design includes five superimposed layers with a centrally-positioned electrolyte connecting two oxide films—at least one of which having EC properties—and with transparent electrical conductors surrounding the three-layer structure in the middle. It is emphasized that this construction can be viewed as a thin-film electrical battery whose charging state is manifested as optical absorption. Also discussed are six well known hurdles for the implementation of these EC devices, as well as a number of practical constructions of EC-based smart windows. [Section 4](#) is an in-depth discussion of various aspects of EC oxides. It begins with a literature survey for 2007–2013, which updates earlier reviews, and is followed by a general discussion of optical and electronic effects and, specifically, on charge transfer absorption in tungsten oxide. Ionic effects are then treated with foci on the inherent nanoporosity of the important EC oxides and on the possibilities to accomplish further porosity by having suitable thin-film deposition parameters. A number of examples on the importance of the detailed deposition conditions are presented, and [Section 4](#) ends with a presentation of the EC properties of films with compositions across the full tungsten–nickel oxide system. [Section 5](#) is devoted to transparent electrical conductors and electrolytes, both of which are necessary in EC devices. Detailed surveys are given of transparent conductors comprising doped-oxide semiconductors, coinage metals, nanowire meshes and other alternatives, and also of electrolytes based on thin films and on polymers. Particular attention is devoted to electrolyte functionalization by nanoparticles. [Section 6](#) considers one particular device construction: A foil that is suitable for glass lamination and which, in the author's view, holds particular promise for low-cost large-area implementation of EC smart windows. Device data are presented, and a discussion is given of quality assessment by use of $1/f$ noise. The "battery-type" EC device covered in the major part of this critical review is not the only alternative, and [Section 7](#) consists of brief discussions of a number of more or less advanced alternatives such as metal hydrides, suspended particle devices, polymer-dispersed liquid crystals, reversible electroplating, and plasmonic electrochromism based on transparent conducting oxide nanoparticles. Finally, [Section 8](#) provides a brief summary and outlook. The aim of this critical review is not only to paint a picture of the state-of-the-art for electrochromics and its applications in smart windows, but also to provide ample references to current literature of particular relevance and thereby, hopefully, an easy entrance to the research field.

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1. Introduction

Smart windows are able to control the throughput of visible light and solar radiation into buildings and can impart energy efficiency as well as human comfort by having different transmittance levels depending on dynamic needs. This critical review discusses oxide-based electrochromic (EC) smart windows with emphasis on recent work related to thin films and their uses for large-area fenestration. Smart windows are currently being used in an increasing number of buildings, and Fig. 1 shows two examples of multi-pane installations in which some panes are in their fully colored state and others are bleached. We note that electrochromism belongs to the “green” nanotechnologies that are very much in focus today [1–3].

We first note that the flat glass market is immense by any standards; the annual production is predicted to reach a stunning 9.2 billion square meters per year in 2016 [4]. Most of this is high-quality glass made by the float process [5] and suitable as substrates for surface coatings. Applying coatings to only a small fraction of this glass in order to make EC smart windows will open up a huge new market for thin solid films.

In Section 1.1, we first consider why “green” nanotechnologies are of interest at present and then, in Section 1.2, we look at the electromagnetic radiation in our natural surroundings with the object of delineating a basis for treating energy efficient fenestration. Section 1.3 provides some remarks on the energy efficiency and other benefits of EC smart windows.

1.1. Setting the scene: people, energy, buildings and windows

We start by looking at the world's population and its interrelationship to our common environment. The population has increased from approximately one billion in 1800 to some 2.5 billion in 1950 and is presently

(2014) about seven billion. The growth is not forecasted to level off until around the year 2100, at a magnitude of ten billion or more [6,7]. Paralleling this population explosion there has been an improvement in overall living standards, and people in the poorer countries expect—as they should—to enjoy the same qualities of life and amenities that we are used to in the more affluent countries. The result of this evolution is that the strains on the global resources are growing steeply and that there is an unsustainable demand on resources of all kinds: energy, water, minerals, etc. Energy is mainly derived from the burning of coal, oil and gas with ensuing injection of carbon dioxide into the air. This change of the atmosphere leads to a depressing list of dangers: global warming, rising sea level, harsher weather, growing likelihood for the spreading of diseases, mass migrations, increased numbers of violent conflicts, negative impacts on global food security, abrupt shifts in the Earth's biosphere, etc. A selection of references to authoritative work on these dangers includes Refs. [8–20]. “The Great Climate Experiment” is a term sometimes used to describe today's precarious situation [21]. Sea levels are particularly well documented and rise by 3.3 ± 0.4 mm per year. This increase is caused by melting glaciers and ice caps [22,23], thermal expansion of the warming water and groundwater depletion. Among the abrupt environmental shifts, one may point at thawing permafrost with associated release of gigantic quantities of CO_2 [24,25] and ocean acidification with ensuing damage to calcifying organisms including corals and foraminifera [26,27]. In principle, nuclear energy could bring huge amounts of CO_2 -free energy and thereby alleviate global warming but, as is too well known, this source of energy is fraught with severe security and health issues [28].

The effect of global warming due to greenhouse gases such as CO_2 is aggravated by the fact that about half of the world's population now lives in cities, and the booming of mega-cities is fast and leads to “urban heat islands” with temperatures several degrees above those of the surrounding countryside [29–33].

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