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ScienceDirect
Solar Energy Materials & Solar Cells 92 (2008) 203–208
Solar Energy Materials and Solar Cells
www.elsevier.com/locate/solmat

Invited paper

Oxide electrochromics: Why, how, and whither

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Received 30 September 2006; accepted 15 October 2006
Available online 24 October 2007

Abstract

Electrochromic oxides form the basis of "smart windows" which are able to provide energy efficiency and indoor comfort simultaneously. This paper attempts to give an introduction to "smart windows" technology, which finally seems to be ready for large-scale applications. The "whys" and "hows" are discussed from the viewpoints of materials, device technology, low-cost manufacturing aspects, and applications to buildings as well as niche products. Furthermore, there are some speculations as to the "whithers" of oxide electrochromics for applications to buildings of the future.

Keywords: Electrochromics; Smart window; Thin film

1. Introduction

The radiation in our natural surroundings is characterized by three general features: spectral selectivity, angular dependence, and temporal variability. Looking first at spectral selectivity, the solar radiation incident on the atmospheric envelope is confined to the $0.2<\lambda<3\,\mu m$ wavelength interval, whereas thermal radiation at normal temperatures lies at $2<\lambda<50\,\mu m$ and visible light as well as light for photosynthesis lie at $0.4<\lambda<0.7\,\mu m$. The atmosphere is largely transparent at $0.3<\lambda<3\,\mu m$, and at $8<\lambda<13\,\mu m$ if the humidity/cloudiness is low. These facts give a multitude of options for the development of solar energy materials with optimized values of absorptance A, transmittance T, reflectance R, and emittance E [1,2]. For example, efficient solar heating demands, ideally, $A=1$ for $0.3<\lambda<3\,\mu m$ and $E=0$ for $3<\lambda<50\,\mu m$, and efficient cooling via radiation to the clear sky demands $R=1$ for $0.3<\lambda<8$ and $13<\lambda<50\,\mu m$ while $E=1$ should prevail for $8<\lambda<13\,\mu m$. Considering windows in buildings, $T=1$ at $0.3<\lambda<3\,\mu m$ and $E=0$ for $3<\lambda<50\,\mu m$ give maximum solar heating jointly with thermal insulation for double glazing, while $T=1$ for $0.4<\lambda<0.7\,\mu m$ and $R=1$ for $0.7<\lambda<50\,\mu m$ give full day lighting at minimum solar heating. Solar-driven air cleaning can be accomplished with photo-catalysts absorbing at $0.3<\lambda<0.4\,\mu m$. Optimized angular properties can boost the performance of spectrally selective surfaces. These and other aspects of solar energy materials have been reviewed at length recently [2].

Materials science also gives options to design for temporal variability. This brings us to chromogenic materials [2,3], encompassing photochromic ones (typically darkening under irradiation in the $0.3<\lambda<0.4\,\mu m$ range), thermochromic ones (typically increasing R at $0.7<\lambda<3\,\mu m$ as the temperature exceeds a certain "critical" value that may be at room temperature), "gasochromic" ones (darkening/bleaching under exposure to reducing/oxidizing gases), and electrochromic (EC) ones [4] (changing their absorption at $0.3<\lambda<3\,\mu m$ under charge insertion/extraction). The purpose of this article is to discuss EC technology and its possibilities to revolutionize building technology by allowing rigid or flexible building skins that are able to regulate their throughput of visible light and solar heating in order to combine energy efficiency and indoor comfort. In particular, this technology is capable of alleviating air conditioning loads that are currently much in focus owing to their rapid growth. One example of many is a recent study from Kuwait stating that more than 75% of the electricity is now consumed by air conditioning at peak load, and that the peak load has increased by a factor ~2.5 from 1991 to 2001 [5].

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doi:10.1016/j.solmat.2006.10.027

The present paper is an elaboration of an earlier one [6].

2. The energy efficiency of chromogenic building skins

Modern man normally spends some 90% of his time inside buildings and vehicles, and the quality of the indoor environment hence is of the greatest importance. More and more energy is used to maintain the indoor environment at a level that is both comfortable and healthy. Looking at the EU, some 40% of the energy supply is used for heating, cooling, ventilation, and lighting of buildings, as well as for appliances; in financial terms this corresponds to about 4% of the gross national product [7,8].

The energy efficiency one can accomplish by use of chromogenic building skins has been difficult to come to grips with, partly since the most fundamental function of a window or glass façade—that of providing unmitigated visual contact between indoors and outdoors—has not always been adequately appreciated. From a strict energy perspective it may be beneficial to eliminate the windows, but this is highly detrimental to the well-being and working efficiency of the persons using the building, who normally would rather prefer a panoramic view of their ambience. Energy efficiency of the windows hence must be reached with an understanding of their need to give transparency.

The energy efficiency of chromogenic building skins (often referred to as "smart windows" [9]) has been investigated in recent simulations [10,11]. Specifically, calculations for a standard office module with well-defined size, window area, lighting demand, occupancy, equipment, etc., showed that the energy savings potential was considerable for the cooling load. The studied office block was oriented with one façade facing South and one facing North, and the simulations were performed with climate data applicable to Rome (Italy), Brussels (Belgium), and Stockholm (Sweden). When using "smart windows" instead of conventional static solar control windows, the energy for space cooling, on an annual basis, could be reduced by as much as 40–50%. The amount of saved energy is obviously climate dependent. In moderately warm climates, such as those of Brussels and Stockholm, the number of days with very high outdoor temperatures is relatively small but the energy required for balancing excessive solar energy inflow nevertheless is substantial, and an interesting result of the simulations was that the cooling power could be reduced so that air conditioning might be completely avoided when "smart windows" are used, thus indicating that the marginal cost for "smart windows" can be more than balanced by the elimination of an air conditioning system. Similar analyses can be made with regard to vehicles [12].

An alternative "back-of-an-envelope-analysis" of the energy efficiency [13] can be made by first setting the solar energy falling onto a vertical surface per year to 1000 kWh/m^2. This represents a nominal value, and more correct numbers for south-facing/north-facing/horizontal surfaces are 850/350/920, 1400/450/1700, and 1100/560/1800 kWh/m^2 for Stockholm (Sweden), Denver (USA), and Miami (USA), respectively. Half of this, i.e., 500 kWh/m^2, is visible light. This latter number is used in the analysis since infrared radiation can be eliminated—at least in principle—by use of known technology for "solar control" that does not require variable transmittance [14,15]. If the transparency can be altered between 7% and 75% [11]—which is by no means unlikely given further EC technology development—the difference between having the window constantly colored and constantly bleached is 340 kWh/m^2. Actually, the stated range of optical modulation can be accomplished today [13] but at the expense of slow coloration dynamics and some degradation under extended cycling.

The next issue is then to contemplate when the "smart window" should be colored and when it should be bleached. With physical presence of persons as the basis of the control strategy, the question is when a room is in use—or, more precisely, the fraction of the solar energy that enters when nobody is present. Considering that a normal (office) room is empty during vacations, holidays and weekends, early mornings and late afternoons (when the Sun stands near the horizon), etc., it may be a conservative estimate that 50% of the energy enters when no one is present to look through the window. This estimate then yields that 170 kWh/m^2 is the amount of energy *saved* annually by adopting the given control strategy. In order to answer the question whether this saving is significant or not, one can note that 17% is a typical value for today's best thin-film solar cells and submodules [16]. Thus, these solar cells would be able to *generate* 170 kWh/m^2 if they were to replace the "smart window" in the example. Clearly, the analogy between energy *savings* in "smart windows" and energy *generation* in solar cells is not tied to the choice of the incident solar energy being 1000 kWh/m^2 but applies generally irrespectively of the orientation of the surface under examination. The "smart window" saves thermal energy, but if a cooling machine for providing comfort cooling—operating with an efficiency of 300%, say—runs on electricity generated with an efficiency of 33% then the analogy becomes perfect. This latter consideration implies that one employs a "national scenario" for the energy, with a "coefficient-of-performance" ("COP-factor") equal to unity.

The analyses above are simplistic and certainly do not capture all of the aspects and assets of the EC "smart windows". A recent analysis at the Lawrence Berkeley Laboratory pointed at the multiple benefits of EC "smart windows"—including subjective ones—and emphasized the importance of adequate control strategies [17,18].

3. Electrochromic device design and materials

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 foil, or positioned between two such substrates in a laminate configuration [4]. The outermost