Oxide-based electrochromics for energy efficient buildings: Materials, technologies, testing, and perspectives

C G Granqvist¹, A Azens², J Smulko³ and L B Kish⁴

¹ Department of Engineering Sciences, The Ångström Laboratory, Uppsala University, P O Box 534, SE-75121 Uppsala, Sweden
² ChromoGenics Sweden AB, Märtstagan 4, SE-75323 Uppsala, Sweden
³ Faculty of Electronics, Telecommunications and Informatics, Gdańsk University of Technology, ul. G. Narutowicza 11/12, 80-952 Gdańsk, Poland
⁴ Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843-3128, USA

Email: claes-goran.granqvist@angstrom.uu.se

Abstract. Electrochromic oxide films form the basis of “smart windows”, which are of much interest in forthcoming building technology and are able to provide energy efficiency and indoor comfort simultaneously. This paper introduces “smart windows” technology, which now seems ready for large-scale applications. Electrochromics is discussed from the viewpoints of materials, device design, low-cost manufacturing, and applications to buildings as well as some niche products. Finally there are some perspectives on the future role of oxide electrochromics in the built environment.

1. Introduction

Radiation in our natural surroundings is characterized by three general features: spectral selectivity, angular dependence, and temporal variability. Beginning with 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 is at 0.4 < \( \lambda \) < 0.7 \( \mu \)m. The atmosphere is transparent in the main part of the 0.3 < \( \lambda \) < 3 \( \mu \)m and at 8 < \( \lambda \) < 13 \( \mu \)m ranges if the humidity/cloudiness is low. These facts of our ambience lead to many 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 requires, 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 good thermal insulation; for double glazing, the heat transfer is about half of what it would have been without minimization of \( E \). Having \( T = 1 \) for 0.4 < \( \lambda \) < 0.7 \( \mu \)m and \( R = 1 \) for 0.7 < \( \lambda \) < 50 \( \mu \)m, on the other hand, gives full day-lighting and good thermal insulation at minimum solar heating (about half of the heating without near-infrared reflectance). Optimized
angular properties can boost the performance of spectrally selective surfaces, and means to diminish the conductive and convective heat transfer between panes can enhance the thermal insulation. These and other aspects of solar energy materials have been reviewed in some detail recently [2].

Materials science also gives possibilities to design for temporal variability as a way to enhance the energy efficiency of windows above what is possible with materials having optimized “static” spectral and angular-dependent properties. The temporal variability can be achieved by use of “chromogenics” [3], encompassing photochromic materials (typically darkening under irradiation in the 0.3 < \( \lambda \) < 0.4 \( \mu m \) range), thermochromic thin films (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” films (darkening/bleaching under exposure to reducing/oxidizing gases), and electrochromic (EC) multilayer structures [4] (changing their absorption at 0.3 < \( \lambda \) < 3 \( \mu m \) under charge insertion/extraction). The purpose of this paper is to briefly outline electrochromics and discuss 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. In the EU(15), the growth has been some 17 % per year between 1995 and 2003 [5], and presently air conditioning dominates the electrical peak load at certain locations and time periods in Southern Europe as well as elsewhere. One extreme example can be found in a recent study from Kuwait reporting that more than 75 % of the electricity is now consumed by air conditioning at peak load, and that this load has increased by a factor ~2.5 from 1991 to 2001 [6]. The present article is adapted from an earlier conference report [7].

2. Comments on Energy Efficiency of Chromogenic Building Skins

Modern Man normally spends 80 to 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 this environment at a level that is both comfortable and healthy. Looking again at the EU(15), some 40 % of the energy supply is currently used for heating, cooling, ventilation, and lighting of buildings, as well as for appliances. In financial terms this corresponds to ~4 % of the Gross National Product [8,9]. Clearly there is much to gain by developing technologies to regulate solar and light flows with minimum energy expenditure, to enable “ventilation on demand” by implementing efficient sensors for air quality, to use solar energy for air cleaning and deodorization so that energy is not wasted by forcing unnecessary air exchanges, etc. From a materials perspective, there are several common traits of the technologies allowing these gains; for example all of them can benefit from nanocrystalline and nanoporous coatings of transition metal oxides [10].

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” [11]—have been investigated in some recent simulations [12-15]. 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 [12]. 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 with large near infrared reflectance, the energy for space cooling, on an annual basis, could be reduced by as much as 40 to 50 %. An interesting result of the simulations was that the cooling power could be reduced so that air
conditioning might be avoided in Northern and Middle Europe 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. Large energy savings were inherent also in another recent study [13,14], which also emphasized a number of important subjective assets of the technology [15]. Similar analyses can be made with regard to vehicles [16].

An alternative “back-of-an-envelope-analysis” of the energy efficiency [17] is best expressed as an analogue between smart windows and today’s best solar cells, having the same size and orientation: the solar cells can generate a certain amount of energy, which is similar to the energy savings the “smart windows” can provide.

3. Electrochromic Device Design and Materials

Figure 1 illustrates a typical EC device and its associated electronics unit. There is an obvious principle resemblance to a thin-film electrical battery. 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 layers are transparent electrical conductors, typically of In$_2$O$_3$:Sn (i.e., Indium Tin Oxide, ITO) [18]. One of these layers is coated with an EC film, whereas the other is coated with an ion storage film which may or may not exhibit EC properties. Both of these films must consist of nanomaterials with well specified nanoporosities (analogously with the case of battery electrodes). A transparent ion conductor (electrolyte) constitutes the central part of the device and joins the EC and ion storage films. A voltage pulse between the transparent electrodes leads to charge being shuttled between the EC and ion storage films, and the overall transparency is thereby changed. A voltage pulse with opposite polarity—or, with suitable material combinations, short circuiting—makes the device regain its original properties. The optical modulation requires a DC voltage of as little as 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.

![Electrochromic device and associated drive circuitry. Ion movement under the action of an electric field is indicated](image)

Regarding materials in EC devices, the ITO can be replaced by ZnO:Al, SnO$_2$:F, or similar oxides (or, possibly, carbon nanotubes) [19-21]. SnO$_2$:F is interesting since it can be made by low-cost spray deposition onto the hot glass as it comes out from a float line. 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 [22], but it has also been claimed that the availability is much too low to allow widespread deployment of indium-containing thin film solar cells [23].

The EC film is WO$_3$-based in almost all devices for window applications, whereas there are many possibilities for the counter electrode [4,24,25]. As to the specific optical absorption mechanism, polycrystalline WO$_3$ can be described in terms of polaron absorption [26,27], which is consistent with recent temperature-dependent angle-resolved photoemission data for Na$_x$WO$_3$ [28]. However, the situation is less clear for the amorphous material, and a traditional polaronic model has been questioned in recent quantum chemical modeling [29]. Regarding counter electrodes, 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$_2$O$_5$ [30]. NiO-based films combine moderate cost with excellent optical properties, especially when the NiO is mixed with another oxide characterized by a wide band gap such as MgO or Al$_2$O$_3$ [31,32]. The electrochromism is essentially a surface effect and involves valence changes on boundaries of nanosized grains. EC devices can use many different electrolytes, either being hydrous oxides exhibiting proton conduction or polymers with ion conduction due to added salts.

EC devices have been discussed a long time, ever since the display-type devices presented shortly after the discovery of electrochromism in WO$_3$ films [33,34]. Generally speaking, the progress of technologies based on electrochromism has been slow, which may be associated with the necessity of simultaneously mastering a range of non-conventional technologies as follows:

(i) The ITO must combine excellent electrical conductivity with very low optical absorption, which is challenging especially for films on temperature sensitive substrates such as polymers [7]
(ii) The EC and counter electrode films must exhibit well specified nanoporosities over large areas, which require non-standard coating technologies
(iii) Viewing the EC device as a “thin film battery” makes it evident that charge insertion/extraction and charge balancing must be accomplished by properly controllable and industrially viable techniques, such as gas treatments [35]
(iv) The electrolyte must combine good ion conductivity with adhesiveness and high transparency for ultraviolet irradiation
(v) Long-term cycling durability demands adequate strategies for voltage and current control during coloration/bleaching—just as it does for charging/discharging of batteries

All of these challenges can be successfully met, however, and EC technology finally may emerge as suitable for large-area, large-scale applications [32,36].

Film porosity on the nanoscale is necessary for the EC film(s), as stressed above. Most thin film technologies may be capable of achieving the desired properties with more or less difficulty. Sputtering is a deposition technique of particular interest since it has proven upscaling capabilities and hence is industrially viable. The properties of sputter deposited films are usually discussed in terms of a “Thornton diagram” [37] which shows schematically what a thin film looks like under the electron microscope. Nanocrystallinity and nanoporosity are found at high pressures in the sputter plasma and at low substrate temperature. In this case it is possible to have ion conduction in the inter-columnar spaces, as required in EC films and in solid state ionic films in general. The specific nanotopography then accomplished has been referred to as “parallel penniform” at least in the case of TiO$_2$ films [38]. However, sputter deposited thin films most often are prepared under conditions with low pressures in the plasma and elevated substrate temperatures. Such films are compact and it is possible to minimize grain-boundary scattering of the conduction electrons in a metallic film. The transparent conducting ITO films in EC devices should be of this character [39].
4. Properties and Applications of Electrochromic Foil

Figure 2 shows recent characteristic data for a 5 x 5 cm$^2$ flexible EC foil incorporating WO$_3$, NiO modified by addition of a wide band gap oxide such as MgO or Al$_2$O$_3$, PMMA-based electrolyte, and ITO films [32,40,41]. The mid-luminous transmittance ($T_{550}$, where the subscript denotes wavelength in nanometers) rapidly attains ~68% upon bleaching and drops to ~36% during a coloration period of 50 s. Still lower values can be reached with extended coloration times. The modulation is smaller, but still significant, for blue light ($T_{400}$) whereas it is larger for red light ($T_{775}$). The substantial transmittance at the ultraviolet end of the spectrum is associated with the oxide added to the NiO. Durability was demonstrated for several tens of thousands of coloration/bleaching cycles. The open circuit memory was found to be excellent, and the optical properties could be maintained virtually unchanged for many hours on end without “refresh” pulses, which clearly is of importance for energy conserving devices.

![Figure 2](image.png)

**Figure 2.** Time-dependent transmittance during coloration/bleaching of an electrochromic device, recorded at three wavelengths.

Quality measures for EC devices are of obvious interest for assessing practical usefulness of “smart windows” and other EC devices. Long-term testing is an option, ideally under some type of accelerated yet reliable conditions [42,43], but there is a clear need for other, faster techniques. One possibility may be offered by low-frequency current noise [44], which was investigated recently in a device of the type discussed above [45]. Figure 3 shows experimental current power spectral density $S_i$ as a function of current $I$ at a frequency $f$ of 700 Hz during the final stage of discharging of an EC device. It is found that $S_i(f) \sim f^2$. The most interesting feature of Fig. 3 is that amplitude of $S_i$ was increased after cycling of the EC device so as to deliberately cause some degradation manifested in irreversible coloration. The result is hardly surprising since current noise of $1/f$ type has been earlier demonstrated to provide useful information on corrosion processes [46-48].

The EC foil can be used for a variety of applications in buildings, vehicles, etc. It can be suspended between glass panes, used as a conventional add-on window film, or employed as a lamination material between rigid glass or polymer panes. The latter application can provide impact resistance, spall shielding during breakage, acoustic damping, etc., as added benefits. The left-hand panel of Fig. 4 shows a prototype “smart window” with four 30 x 30 cm$^2$ EC foils mounted between glass panes. The upper two panels are fully colored while the lower two are fully bleached. Each of the panels can shift gradually and reversibly between the dark and transparent states in about a minute, *i.e.*, during the time it takes for the eye to adapt to different lighting conditions. It is important to note
that the window maintains its primary function—that of providing unmitigated visual indoors/outdoors contact—irrespective of the state of coloration. The windows cannot give privacy, though.

Potential applications in energy efficient buildings and automobiles have provided the main impetus for research and development on electrophochromics for several years. However, there are numerous other applications as well, especially with regard to foil-type devices. These can be applied, for example, in ski goggles and visors for motorcycle helmets. The visors can be colored to a chosen degree in the day and bleached in the night. It is especially important that the driving and riding safety can be improved by having the visor bleach before entering tunnels or other dark spaces. Another aspect with a bearing on safety is that facial warming can be significantly limited by absorption in the visor [49]. The right-hand panel of Fig. 4 illustrates a visor in a motorcycle helmet.

Figure 3. Current noise power spectra, denoted $S(f)$ where $f = 700$ Hz, as a function of current $I$ during the final stage of discharging of an EC foil based on WO$_3$ and NiO. Data are shown before and after harsh color/bleach cycling to give device degradation. The lines denote $I^2$ dependencies.

Figure 4. “Smart window” prototype with four 30 x 30 cm$^2$ panels (left) and electrochromic visor for a motorcycle helmet in colored and bleached states (right).
5. Conclusion and Perspectives

Electrochromism was discovered and made publicly known many years ago [33,34]. However, the progress of EC device technology has been slow. A number of reasons for this were given above. Buildings with “smart windows” based on electrochromism have been tried by the glass and coatings industry for decades, and more or less encouraging results have been reported. For one reason or another, these “smart windows” have not made it to the market. Today, however, the scene seems to be changing and EC roof windows for buildings [50] as well as EC car roofs [51] are available on a limited commercial scale. These EC devices use glass as a base, implying that large substrates and expensive coating units must be used. But cheap production of EC devices is necessary if the technology will be used elsewhere than in niche markets. An alternative route, using web coating by technologies allowing roll-to-roll manufacturing, is now employed for EC prototypes. This EC foil was discussed above.

What about the future of electrochromics? Windows with tunable optical properties have long been something of a Holy Grail in “high-tech” architecture [52]. Electrically regulated EC “smart windows” are particularly interesting in view of their potential to provide user-related operation. Such windows make it possible to combine increased indoor comfort for the occupant of the building (less glare and thermal stress) with large energy efficiency (especially lowered air conditioning load in cooled spaces), as emphasized above. Therefore, there is a strong incentive for their introduction. Durability, optical switching speed, and size constraints constitute an interrelated problem complex which is not fully solved today. However consensus is growing that a satisfactory solution can indeed be achieved. Cost is another major concern, but recent progress in manufacturing technology—such as roll-to-roll coating of polymer foil—appears to open new avenues towards inexpensive products. It should also be realized that electrochromism is an enabling technology of relevance for a vast number of applications so there may be multiple roads towards devices eventually used in buildings.

The EC technology may be combined with facilities to direct daylight deeply into buildings by use of light-guiding devices. By equalizing the light level in a room, the eye—which tends to adjust to the brightest illumination—does not perceive deeper regions as disturbingly dark, and hence there is less need for artificial lighting. Similar notions, though employing a Venetian blind system, have been discussed recently [53,54]. Generally speaking, the EC technology leads to new vista in day-lighting, which is generally regarded as superior to artificial lighting by giving better task performance, improved visual comfort, and positive mood effects, especially if glare problems are eliminated [55]. Particularly beneficial effects have been observed concerning student performance in daylit schools [56] and increased sales in daylit stores [57].

References

[1] Granqvist C G 1981 Appl. Opt. 20 2606
[2] Granqvist C G 2003 Adv. Mater. 15 1789
[3] Lampert C M and Granqvist C G, editors, 1990 Large-Area Chromogenics: Materials and Devices for Transmittance Control (SPIE – The International Society for Optical Engineering, Bellingham, U.S.A.)
[4] Granqvist C G 1995 Handbook of Inorganic Electrochromic Materials (Elsevier, Amsterdam, The Netherlands)
[5] Jäger-Waldau A, editor, 2004 REF-SYST Status Report, EUR 21297 EN (JRC, Ispra, Italy, 2004)
[6] Darwish M A 2005 Kuwait J. Sci. Engr. 32 209
[7] Granqvist C G 2007 Thin Solid Films, to be published
[8] Santamouris M 2001 in Solar Energy: The State of the Art, Gordon J, editor (James & James Sci. Publ., London, UK) pp. 1-28
[9] Reinhart C F 2002 in The Future for Renewable Energy 2 (James & James Sci. Publ., London, UK) pp. 79-114
[10] Granqvist C G, Azens A, Heszler P, Kish L B and Österlund L 2007 Solar Energy Mater. Solar Cells 91, 355
[11] Svensson J S E M and Granqvist C G 1985 Solar Energy Mater. 12 391
[12] Roos A, Persson M-L, Platzer W and Köhl M 2005 in Proc. Glass Processing Days (Tampere, Finland) pp. 566-569.
[13] Lee E S, DiBartolomeo D L and Selkowitz S E 2006 Energy Buildings 38 30
[14] Lee E S, Selkowitz S E, Clear R D, DiBartolomeo D L, Klems J H, Fernandes L L, Ward G J, Inkarojrit V and M. Yazdanian M 2006 Advancement of Electrochromic Windows, CEC-500-2006-052 (California Energy Commission, PIER)
[15] Clear R D, Inkarojrit V and E. S. Lee E S 2006 Energy Buildings 38 758
[16] Jakšić N I and Salahifar C 2003 Solar Energy Mater. Solar Cells 79 409
[17] Azens A and Granqvist C G, J. Solid State Electrochem. 7 64
[18] Granqvist C G and Hultåker A 2002 Thin Solid Films 411 1
[19] Granqvist C G 1991 in Materials Science for Solar Energy Conversion Systems, Granqvist C G, editor (Pergamon, Oxford, UK) pp. 106-167
[20] Hollands K G T, Wright J L and Granqvist C G 2001 in Solar Energy: The State of the Art, Gordon J, editor (James & James Sci. Publ., London, UK), pp. 29-107
[21] Granqvist C G 2007 Solar Energy Mater. Solar Cells, to be published
[22] U. Schwartz-Schampera U and Herzig P M 2002 Indium: Geology, Mineralogy, and Economics (Springer, Berlin, Germany)
[23] Feltrin A and Freundlich A., to be published.
[24] Granqvist C G 2000 Solar Energy Mater. Solar Cells 60 201
[25] Granqvist C G, Avendaño E and Azens A 2003 Thin Solid Films 442 201
[26] Larsson A-L, Sernelius B E and Niklasson G A 2003 Solid State Ionics 165 35
[27] Edéth J, Hoel A, Niklasson G A and Granqvist CG 2004 J. Appl. Phys. 96 5722
[28] Raj S, Hashimoto D, Matsui H, Souma S, Sato T, Takahashi T, Ray S, Chakraborty A, Sarma D D, Mahadevan P, McCarror W H and Greenblatt M 2005 Phys. Rev. B 72 125125
[29] Broclawik E, Góra A, Liguzinski P, Petelenz P and Witek H A 2006 J. Chem. Phys. 124 054709
[30] Backholm J, Azens A and Niklasson G A 2006 Solar Energy Mater. Solar Cells 90 414
[31] Avendaño E., Azens A, Niklasson G A and Granqvist C G 2004 Solar Energy Mater. Solar Cells 84 337.
[32] Niklasson G A and Granqvist C G 2007 J. Mater. Chem. 17 127
[33] Deb S K 1973 Philos. Mag. 27 801
[34] Deb S K 1995 Solar Energy Mater. Solar Cells 39 191
[35] Azens A, Kullman L, and Granqvist C G 2003 Solar Energy Mater. Solar Cells 76 147
[36] Granqvist C G 2006 Nature Mater. 5 89
[37] Thornton J A 1977 Ann. Rev. Mater. Sci. 7 239
[38] Rodriguez J, Gómez M, Lu J, Olsson E and Granqvist C G 2000 Adv. Mater. 12 341
[39] Hamberg I and Granqvist C G 1986 J. Appl. Phys. 60 R123
[40] Azens A, Gustavsson G, Karmhag R and Granqvist C G 2003 Solid State Ionics 165 1
[41] Azens A, Avendaño E, Backholm J, Berggren L, Gustavsson G, Karmhag R, Niklasson G A, Roos A and C. G. Granqvist C G 2005 Mater. Sci. Engr. B 119 214.
[42] Lampert C M, Agrawal A, Baertlchien C and Nagai J 1999 Solar Energy Mater. Solar Cells 56 449
[43] Bell J M and Skryabin I L 1999 Solar Energy Mater. Solar Cells 56 437
[44] van Kampen N G 1992 Stochastic Processes in Physics and Chemistry (Elsevier, Amsterdam, The Netherlands).
[45] Smulko J, Azens A, Kish L B and Granqvist C G 2007 to be published
[46] Cottis R A 2006 *Elektrokhim*. 42 557 [English translation *Russian J. Electrochem.* 42 497]
[47] Smulko J 2006 *Fluctuation Noise Lett*. 6 R1
[48] Smulko J M, Darowicki and Ziełniński Z 2006 *Elektrokhim*. 42 611 [English translation *Russian J. Electrochem.* 42 546]
[49] Buyan M, Brühwiler P A, Azens A, Gustavsson G, Karmhag R and Granqvist C G 2005 *Int. J. Ind. Ergon*. 36 11
[50] Sbar N L and Sanders H E 2005 *Proc.s 48th Ann. Tech. Conf.* (Soc. Vacuum Coaters, Albuquerque, U.S.A.) pp. 679-680
[51] D. Pender D and Giron J-C 2005 *Abstract Volume, Fall Meeting, Mater. Res. Soc.*, (Warrendale, U.S.A.), p. 110.
[52] Wigginton M 1996 *Glass in Architecture* (Phaidon, London, UK)
[53] Beltrán L O, Lee E S and Selkowitz S E 1997 *J. Illumination Engr. Soc.* 26(2) 91
[54] Martins-Mogo B G and Beltrán L O 2006 *Conf. Proc: EuroSun 2006*, Glasgow, UK, Burek S, Hutchins M G, Lockhart-Ball H and Abrahamson S, editors (The Solar Energy Society, Abingdon, UK)
[55] Gligor V 2004 *The Luminous Environment and Office Productivity* (Tech. Lic. Thesis, Dept. Electr. Commun. Engr, Helsinki University of Technology, Espoo, Finland)
[56] Heshong L, Wright R L and Okura S 2002 *J. Illum. Engr. Soc*. 31 101
[57] Heshong L, Wright R L and Okura S. 2002 *J. Illum. Engr. Soc* 31 21