

Tutorial

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Optical coatings for energy-efficient fenestration: principles, products and prospects

Abstract: Buildings use as much as 40% of the world's total primary energy. This huge energy consumption is mainly tied to poor designs and entrenched practices for buildings' envelopes. One major road toward more energy efficient buildings is to employ design principles that are in harmony with the radiation in our natural surroundings. Glass coatings with spectral selectivity can lead to windows and glass facades with good thermal insulation and capability to transmit mainly visible light or, alternatively, across the full solar spectrum. Chromogenic glazings, especially if based on electrochromism, can regulate the inflow of visible light and solar energy between widely separated limits and achieve further energy efficiency. The new fenestration technologies are able to improve indoor comfort.

Keywords: energy efficient buildings; glazings; optical coatings; spectral selectivity.

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1 Introduction: the quest for better buildings

Optical coatings on windows are used on a huge and rapidly increasing scale. To grasp the immensity of the market, one should ponder that the annual production (2012) of flat glass is about 6 billion square meters, and that this production is forecast to increase by approximately 6% per year [<http://www.freedoniagroup.com/World-Flat-Glass.html>]. Most of the flat glass is made by the float process, has high quality, and is suitable for surface coating and implementation in windows and glass facades (referred to jointly as 'glazings').

The current acute interest in coatings for glazings is connected with today's demand for energy-efficient buildings and, more generally, a sustainable and eco-efficient future [1, 2]. Indeed, 30% to 40% of the world's primary energy is used in buildings worldwide – for heating, cooling, lighting, ventilation, and appliances – and this fraction is growing in many countries [3]. In the USA, to take one example, the building sectors' part of the primary energy consumption was 41% in 2010, which can be compared with 34%, 36%, and 38% in 1980, 1990, and 2000, respectively [4]. The fraction of the electricity that is used in buildings is even higher and amounts to about 70% for the richest countries [5]. It should also be remembered that fractions do not say everything and may even be misleading, and the total global energy consumption rises steeply as the world's population is increasing, and the general standard of living improves, particularly in some of the world's largest countries such as China and India. Of course, buildings are important also from a purely human perspective, and they are where we live most of our lives; the part of the time we spend indoors, in buildings and vehicles, is often as large as 80–90%, at least in the most industrialized countries [6]. New buildings are often less wasteful in terms of energy than old ones, and the energy footprint of buildings can certainly continue to drop by the implementation of new and advanced materials. But it should also be kept in mind that, for better or worse, most buildings stay with us for very long times, and a building constructed today probably will be around for a century or so, which means that refurbishment is an important concept for sustainable buildings [2].

Most of the energy that is used in buildings originates from fossil fuels such as coal, oil, and gas. When these fuels are burned, there are huge emissions of carbon dioxide into the atmosphere, which drive global warming and its associated effects such as rising sea levels and numerous strains on the biosphere. The net warming effect is aggravated by the fact that more than half of the world's population now lives in cities, which in themselves lead to local climates that are warmer than those of the surrounding countryside. These 'urban heat islands' can be surprisingly intense, and the temperature rise amount to as much as several degrees under unfavorable weather conditions [7].

The purpose of this tutorial is to explain why optical coatings can lead to very significant improvements in the energy efficiency of glazings, to introduce the basics of today's technologies, and to outline forthcoming technology that already exists as prototypes or is under development in research laboratories. Coating technology, as such, is not included in this tutorial but is covered elsewhere [8].

2 Light, solar energy, thermal radiation, and more

One can develop a good understanding of energy-efficient fenestration by considering the electromagnetic radiation around us [1, 9]. This radiation is conveniently discussed starting with Figure 1, where its various characteristics are introduced with a common logarithmic wavelength scale.

First of all, everything emits electromagnetic radiation and receives radiation. This radiation can be understood by starting with Planck's radiation law, which is a cornerstone in modern quantum physics; its spectrum is governed by the temperature and the surface properties of the radiating object. The four bell-shaped graphs in Figure 1A depict the Planck spectra for some temperatures of practical relevance. The actual emitted radiation is obtained as the Planck spectrum multiplied by an emittance; the emittance is a materials-related property, which, in general, is wavelength dependent. Most things in our surroundings – such as water, soil, rocks, vegetation, concrete, asphalt and, notably, glass – have an emittance of about 0.9, so the curves at the top of Figure 1 are, in fact, good descriptions of the emitted *thermal radiation*. The only important exception is a clean metal surface, which can have an emittance as low as a few percent. However, notwithstanding the magnitude of the emittance, thermal radiation at normal temperatures falls within the $2 < \lambda < 50 \mu\text{m}$ interval, where λ is used to denote wavelength.

Solar radiation is considered next. It comes at wavelengths in the $0.25 < \lambda < 3 \mu\text{m}$ range, as illustrated in Figure 1B. The bell-shape of this curve makes it look like a Planck spectrum and, as a matter of fact, is well described by such a spectrum corresponding to about 5500°C . This temperature is, therefore, taken to be the sun's surface temperature; it is vastly smaller than the temperature of around 15 million degrees, which characterizes the interior of the sun and is a consequence of the nuclear reactions powering the sun. The integrated area under the solar spectrum gives a 'solar constant', which is $1353 \pm 21 \text{ W/m}^2$ and corresponds to the power density on

a surface oriented perpendicular to the solar radiation and located just outside the atmosphere. Already at this point, it is possible to make an important observation: the wavelength regions for incident solar radiation and outgoing thermal radiation are almost nonoverlapping, and it follows that surfaces can have entirely different properties for solar radiation and thermal radiation.

The solar radiation that falls onto a window has traversed the atmosphere, and the radiation that leaves a window goes into the atmosphere. It is obvious that *atmospheric absorptance* is important, and Figure 1C reports the absorptance – from zero to unity – vertically through the full atmospheric envelope for clear weather and at sea level. Most of the solar irradiation can penetrate the atmosphere, and the maximum power density at ground level is 1000 W/m^2 . The shortest wavelengths are characterized by strong atmospheric absorption, which is due to

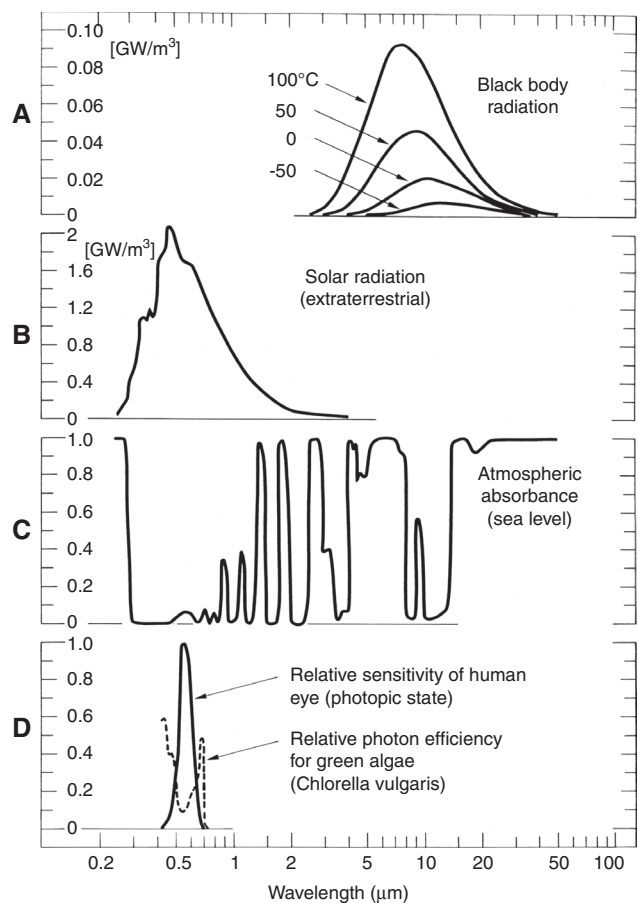


Figure 1 Spectra for radiation in our natural surroundings, showing (A) blackbody radiation from surfaces at 'normal' temperatures, (B) the solar spectrum outside the atmosphere, (C) absorption in the atmospheric envelope during clear weather, and (D) spectral responses for the human eye and for photosynthesis in green plants. From Ref. [9].

ozone. This absorption is good as intense short-wavelength radiation is harmful and may cause melanoma. At long wavelengths, beyond 1 μm , say, one can note a number of strong absorption bands, which are caused by water vapor, carbon dioxide, and ozone. There is a very notable exception, however, and the atmosphere can be highly transparent in the $8 < \lambda < 13\text{-}\mu\text{m}$ range, which is known as the (primary) ‘atmospheric window’. This ‘window’ is open day and night during clear weather conditions; it is located where thermal radiation is peaked and is essential for the earth’s thermal balance and constitutes a main channel for energy loss from the earth. If the amounts of carbon dioxide and/or water vapor are altered in the atmosphere, for example, by introducing vast amounts of carbon dioxide, the ‘window’ gets narrower, the energy loss is smaller, and global warming is the result. We return briefly to the effect of this ‘window’ in Section 6.

Finally, Figure 1D illustrates two important biological facts. The solid, bell-shaped curve is the *eye’s relative sensitivity*, which is confined to $0.4 < \lambda < 0.7\ \mu\text{m}$ and peaked at $0.55\ \mu\text{m}$. The dashed curve in the same panel indicates *photosynthetic efficiency*, which takes place for the same wavelengths as those our eyes can perceive. The photosynthetic sensitivity exhibits a double peak and is qualitatively different from the eyes’ performance. One can now draw an important conclusion: only part of the solar radiation is useful for human vision and for (most) plants. Solar radiation at $\lambda < 0.4\ \mu\text{m}$, i.e., in the ultraviolet, carries some 5% of the solar energy, while radiation at $\lambda > 0.7\ \mu\text{m}$, which lies in the infrared, carries around 50% of the energy. In other words, only the remaining 45% is what our eyes can use. These numbers are of great importance for energy-efficient windows, as we will see shortly.

Summarizing the main features of Figure 1, it is found that well-defined and sometimes non-overlapping wavelength ranges are characteristic for the various types of electromagnetic radiation around us. This is referred to as *wavelength selectivity*, and it leads to many possibilities to create advanced window coatings and other applications. Another key feature for ambient radiation is its *angular selectivity*, which means that radiation is often incident from, or exiting, at a specific wavelength or wavelength range. Direct solar energy impinges onto a window from a point high up on the vault of heaven during most of the day, while visual indoor-outdoor contact is normally along a rather horizontal line-of-sight. It is then realized that one can minimize solar energy inflow into a room while preserving a good view of the surroundings by a conscious use of overhangs, blinds, or nanostructured materials. Finally, it is certainly well known (too well known sometimes) that the weather varies during the day and season,

and sometimes, it may be warm and sometimes cold. This *temporal variability* may demand energy guzzling cooling or heating of buildings, unless one uses materials whose properties can be changed through some external stimulus, for example, to modify the solar energy throughput of windows. Such materials are commonly called *chromogenic* [10] and are discussed further below.

Bringing it all together, nature provides us with a set of ‘rules’ – which involve wavelength selectivity, angular selectivity, and temporal variability – and energy-efficient windows, and sustainable buildings, in general, must work in harmony with these ‘rules’.

We now consider what this means for the optical properties of a window, viz., its absorptance A , reflectance R , transmittance T , and emittance E . Here, A , T , and R denote the fractions of the radiation that are absorbed, transmitted, and reflected, respectively, and E is the fraction of the blackbody radiation that is emitted. Energy conservation requires that

$$A(\lambda) + R(\lambda) + T(\lambda) = 1 \quad (1)$$

and

$$E(\lambda) = A(\lambda) \quad (2)$$

for each wavelength. Eq. (2) is known as Kirchhoff’s law and applies to thermodynamic equilibrium.

3 Energy-efficient windows: on the importance of low thermal emittance and solar control

Indoor and outdoor temperatures are usually different, and hence, it is necessary to heat or cool in order to have a comfortable climate inside a building. Good thermal insulation is required in order not to waste excessive amounts of energy for this heating and cooling. We, therefore, now consider the thermal properties of glazings.

Heat transfer is governed by radiation, conduction, and convection and can be measured and calculated. Figure 2 shows computed data for glazings comprising one, two, and three vertical glass panes separated by air gaps [11]. The glass surfaces are numbered consecutively with the outermost surface labeled 1. One of the surfaces is taken to have an emittance between 0 and 0.85, where the highest value refers to normal glass, which means that the calculation illustrates the role of a lowered surface emittance. The two upper curves in Figure 2, referring to a single glass pane, show that the heat transfer drops somewhat from about

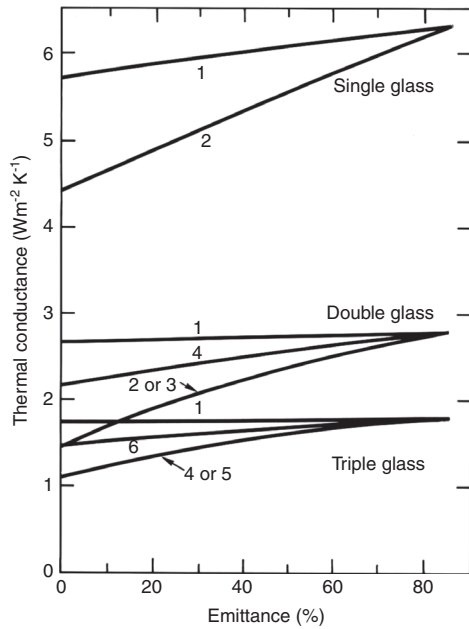


Figure 2 Computed thermal transfer for different glazings with one surface assumed to have a low thermal emittance. The glass surfaces are numbered consecutively with the outermost surface called 1, and the panes are separated by air gaps of 12.7 mm (typical for insulated glass units). The calculations assume a low outdoor temperature as well as some wind and are not described in detail. From Ref. [11].

6 W/m²/K as the surface emittance is lowered. The relative effect of emittance changes is much larger for double and triple glazings, however, and the heat transfer then goes from 2.8 to 1.4 W/m²/K and from 1.8 to 1.2 W/m²/K, respectively, as the emittance approaches 0. It is also found that the low emittance should be on either of the surfaces facing the air gap. One should note that the heat transfer in a double-pane glazing can be almost halved when one of the surfaces exhibits low emittance. (In fact, modern fenestration hardly ever uses air in between the panes; instead, the glazing is an ‘insulated glass unit’ (IGU) and has a gas such as argon confined between the panes, which leads to a further drop of the heat transfer though not at all as significant as the drop caused by a low thermal emittance.)

How can one achieve the desired low emittance for a glass surface? To answer this question one first needs to know something about window glass, which obviously is transparent for visible light and usually also is rather transparent for solar energy, whereas it is opaque for thermal radiation. A low value of E means that A is low, and Eq. (1) shows that the corresponding value of R should be high. This can be achieved by overcoating the glass with a thin layer (usually called a ‘thin film’) with the following ideal property:

$$T(\lambda)=1 \text{ for } 0.4 < \lambda < 3 \mu\text{m} \quad (3a)$$

$$R(\lambda)=1 \text{ for } 3 < \lambda < 50 \mu\text{m} \quad (3b)$$

A practical glazing should be transparent for visible light and have low heat transfer, but what about transparency of solar energy? Figure 1 showed that roughly half of the solar energy falls in the infrared, so the specific question is if this radiation should be transmitted or not. If the building under consideration requires heating (or, more properly, if the room where the glazing is used needs heating) then, the solar energy throughput should be maximized, meaning that the properties delineated in Eq. (3) are wanted. However, many buildings do not require solar heating but rather have a cooling demand, which is true for almost all modern commercial buildings, irrespective of their geographical location, and also for residential buildings in warm climates. Then, the desired property is

$$T(\lambda)=1 \text{ for } 0.4 < \lambda < 0.7 \mu\text{m} \quad (4a)$$

$$R(\lambda)=1 \text{ for } 0.7 < \lambda < 50 \mu\text{m} \quad (4b)$$

Coatings with properties approximated by Eqs. (3) and (4) are referred to as ‘low- E coatings’ and ‘solar control coatings’, respectively. They are electrically conducting, and often alternatively referred to as ‘transparent conductors’; they can be employed as electrodes, for example, in electrochromics (see below), solar cells, and light-emitting diodes.

4 Coatings for ‘low- E and ‘solar control’: materials and characteristic properties

Several types of coating materials can be used to accomplish low thermal emittance and solar control. The most widely used coatings for energy efficient glazings are based on extremely thin metals, in particular silver, and are discussed first. After that, we consider semiconductor-based coatings and a few other alternatives.

What happens when a metal is deposited onto glass or plastic by a technique such as vacuum evaporation or sputter deposition? The surface coating does not grow uniformly, but rather, the growth resembles what happens when water vapor condenses on a fatty surface – though with the difference that the metal ‘droplets’ are on the scale of nanometers to micrometers. Figure 3 shows some scanning electron micrographs for gold films made by sputter deposition onto glass [12]. The thicknesses of the coatings

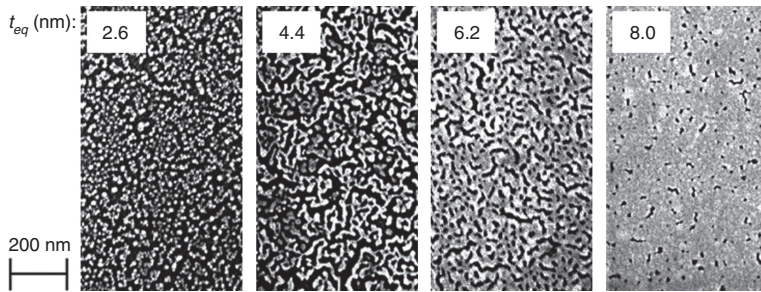


Figure 3 Scanning electron micrographs for gold films made by sputtering onto glass to the shown equivalent thicknesses t_{eq} . The gold appears bright and the uncoated parts of the substrate look dark. From Ref. [12].

are ‘equivalent’ ones, i.e., the thicknesses hypothetical uniform deposits would have. The initial deposition clearly leads to tiny metallic nuclei formed at certain sites on the substrate, and continued deposition makes these nuclei grow, which is expected to take place via diffusion of atoms or molecules over the substrate surface as well as by direct impingement of atoms or molecules. Progressing deposition make some of the ‘islands’ touch and reorganize into larger and more irregular objects; this is usually referred to as ‘coalescence growth’. The growing thin film then passes through what can be termed ‘large-scale coalescence’, meaning that a meandering metallic network of macroscopic extent is formed. It is only now that metallic conduction can be measured along the film, and infrared reflectance sets in. Subsequent deposition makes the voids between the metallic paths become smaller and increasingly regular, and eventually a uniform metal film may form.

A layer of silver or gold, of the order of 10 nm in thickness, can show some optical transparency, which is mainly limited by reflectance at the film’s surfaces. If this thin film is embedded between dielectric layers with well-adjusted thicknesses, its reflection can be strongly diminished via destructive optical interference so that there is a corresponding boost in transmittance. Figure 4 illustrates some representative optical and electrical data, specifically for ZnO/Ag/ZnO three-layer structures with ZnO thicknesses of 20 nm and varying silver thicknesses [13]. The maximum transmittance is larger than 90%. The electrical resistance is high for the smallest silver thicknesses, as very thin metal films are not fully contiguous, but the resistance drops in proportion to the thickness of the silver layer provided that it is larger than about 6 nm.

Hence, carefully prepared silver-based coatings can display high transmittance at short wavelengths, while their reflectance at long wavelengths can be high. The onset of high reflectance takes place at a wavelength that depends on the thicknesses in the dielectric/silver/

dielectric stack (and in more elaborated multilayer structures developed on this theme). Such multilayer structures have widespread applications both for ‘low- E ’ and ‘solar control’ applications. The silver cannot be exposed to air, so it has to be used in insulated glass units typically with argon gas between the glass panes. The electrical resistivity is low and may be on the scale of 10^{-5} to 10^{-6} Ω cm. The left-hand panel in Figure 5 shows the performance of a commercial solar control coating based on silver [14]. It transmits 80% of visible light and 41% of solar energy.

Certain oxides can be used as alternatives to the metal-based coatings, notably those combining a wide optical band gap – i.e., visible transparency – with an ability to achieve good electrical conductivity and, hence, infrared reflectivity. Indium oxide may be the best example; it is transparent, and replacing a few percent of the indium atoms with tin renders the material electrically conducting [15]. The density of the free electrons depends on the tin content and produces metal-like properties for wavelengths

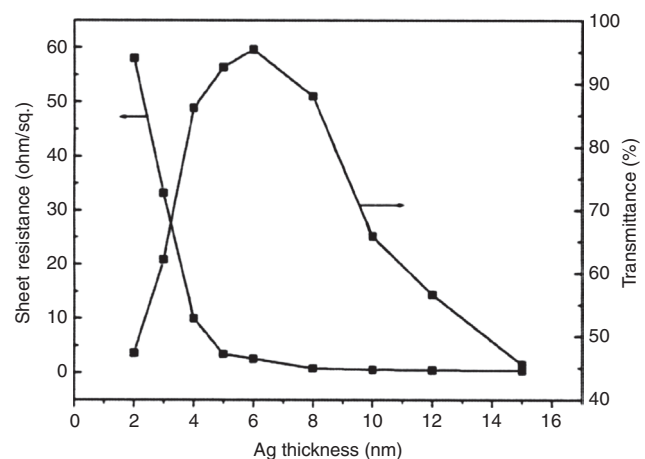


Figure 4 Electrical resistance and maximum optical transmittance vs. Ag thickness in a three-layer structure comprising ZnO (20 nm)/Ag/ZnO (20 nm). From Ref. [13].

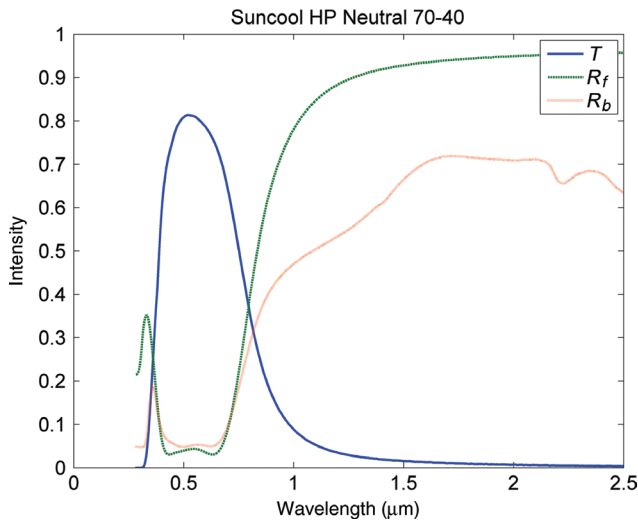


Figure 5 Spectral transmittance T and reflectance from the front (coated) side (R_f) and the backside (R_b) for a commercial silver-based coating optimized for ‘solar control’. From Ref. [14].

beyond a value known as the ‘plasma wavelength’ denoted λ_p . It is possible to prepare indium-tin-oxide coatings so that λ_p lies at about $2\ \mu\text{m}$, which means that the coating can attain low thermal emittance – albeit not as small as a silver-based coating – while the transmittance for solar energy remains high. Thus, the coating can serve for ‘low- E ’ applications but not for ‘solar control’. Alternative coatings are tin oxide containing some fluorine, zinc oxide with aluminum, and others. Tin oxide is particularly hard and rugged and can be put on glass surfaces exposed to air. The electrical resistivity may be as low as $10^{-4}\ \Omega\ \text{cm}$, and typical film thicknesses are a few hundred nanometers. The resistivity can be taken as more or less thickness independent. Figure 6 shows data for a commercial window coating based on tin oxide [9]. The transmittance is 83% for visible light and 71% for solar energy.

Among the emerging alternatives to the metal-based and semiconductor-based coatings mentioned above, we note that carbon can form an infinite number of nanostructures some of which are illustrated in Figure 7 [16]. Graphite comprises weakly bound layers as shown to the right, and if these layers are separated, one gets graphene. Carbon can also form nanotubes, as shown in the middle, and nanoparticles comprising 60 atomic units (C_{60} , called a ‘buckminsterfullerene molecule’ or ‘buckyball’). Single-walled carbon nanotubes, with lengths up to several centimeters, consist of one layer of hexagonal graphite lattice rolled to form a seamless cylinder with a radius up to a few nanometers. These nanowires are of two types: they have metallic or semiconducting properties and electrical conductivities comparable to those of copper and silicon,

respectively. Meshes of such nanowires can serve as transparent conductors with properties approaching those of the oxides mentioned above. Graphene is a fascinating transparent conductor with possibilities for mass manufacturing [17], but its widespread applicability as a coating for glazings is not yet clear (in 2013).

Meshes of silver nanorods is still another transparent conductor that deserves some interest [18]. They are somewhat optically scattering, which limits their applicability for normal glazings, while the scattering can be beneficial for other applications such as in solar cells and light-emitting devices. Large amounts of nanowires, such as those illustrated in Figure 8, can be formed by inexpensive reduction of silver nitrate.

5 More energy-efficient windows: electrochromics and thermochromics

A class of materials known as *chromogenic* can be used to obtain variable optical properties and can be implemented in windows in order to admit or reject solar energy or visible light so as to avoid heating or cooling of buildings and to achieve good daylight indoors [1, 10]. There are two main types of such *smart windows*: the first one is *electrochromic* and uses electricity to change the optical properties [19, 20], and the other is *thermochromic* and responds to temperature changes [21]. Electrochromic

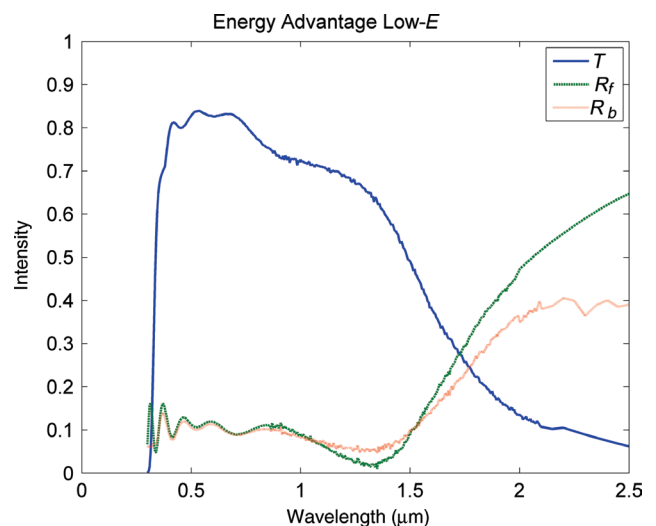


Figure 6 Spectral transmittance T and reflectance from the front (coated) side (R_f) and the backside (R_b) for a commercial tin-oxide-based coating optimized for ‘low- E ’. From Ref. [14].

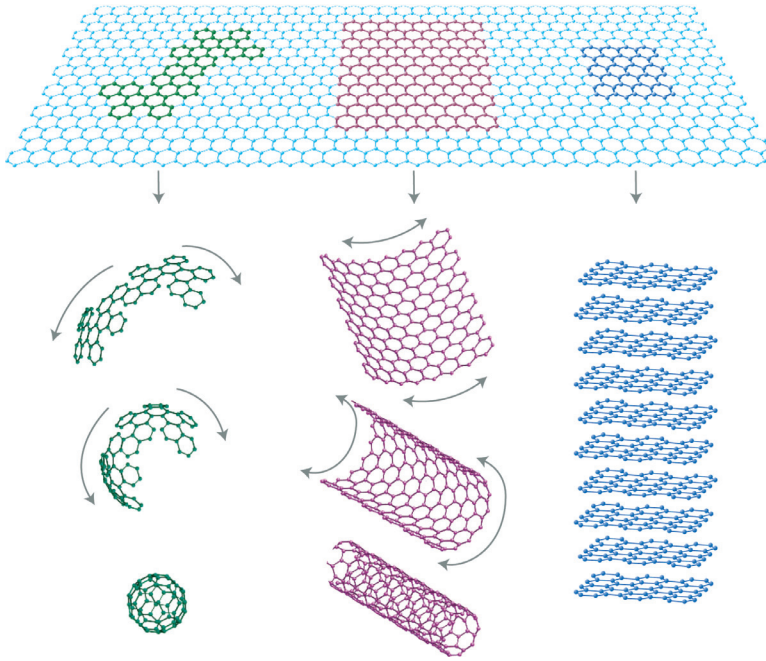


Figure 7 Carbon-based nanostructures and how they are formed. From Ref. [16].

glazings are currently (2013) making their appearance on a limited scale and are expected to become more common in the future [22–24]. Thermochromic glazings are under development as well [25]. These technologies have the capability to change the building from being a static unit requiring large amounts of energy to maintain

a good indoor environment to one that adjusts to varying demands and, hence, acts in harmony with nature.

The right-hand part of Figure 9 illustrates the principle of an electrochromic device. A transparent electrolyte, for example, an ion-conducting polymer, is positioned in the center. This layer joins two nanoporous oxide films,

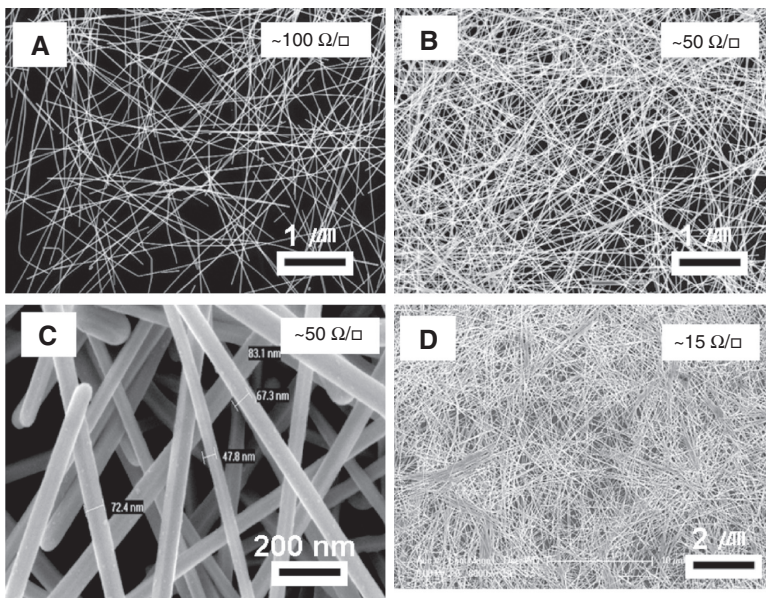


Figure 8 Scanning electron micrographs of silver nanowire meshes with the shown resistance. From Ref. [18].

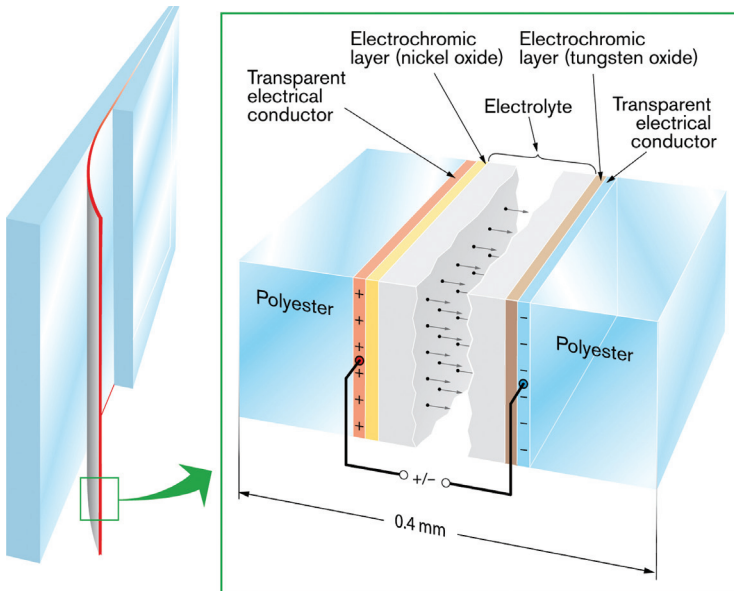


Figure 9 Construction principle for an electrochromic foil-type device implemented as a laminate between glass panes.

for example, of tungsten oxide and nickel oxide. This three-layer stack is located between transparent electrical conductors; any one of the options discussed in Section 4 above can be used, but an oxide-based alternative may be most suitable as it is hard and corrosion resistant. The application of a voltage between the transparent conductors – typically a few volts DC – transfers charge between the tungsten oxide and nickel oxide layers. The operation is akin to that of an electrical battery with tungsten and nickel oxide serving as cathode and anode, respectively. As a matter of fact, it is very instructive to view the electrochromic device as an electrical battery with optical absorption depending on the charging state: the device absorbs across the solar spectrum when the mobile charge is in the tungsten oxide, and it is transparent when this charge is in the nickel oxide. The optical properties can remain unchanged – dark, bleached, or intermediary – for days on end under open-circuit conditions. The optical changes are gradual and take place at a rate that depends on the amount of charge that needs to be transferred, which in practice depends on the size of the device. This response time may be tens of minutes for a large glazing, while an area of a square centimeter may darken and bleach in seconds.

We now consider what causes the optical transmittance changes in some oxides and first note that electrochromism can occur in oxides capable of conducting both electrons and ions [19]. Tungsten oxide is an especially well-known electrochromic material whose atomic structure is shown in Figure 10. This oxide consists of corner-sharing

octahedral units with a centrally positioned tungsten atom surrounded by six oxygen atoms so that the overall composition is WO_3 . The electrochromic oxides also generally have a tendency toward oxygen deficiency, which in the case of tungsten oxide means that some of the octahedra are edge sharing (cf. Figure 10). Contemplating the shown atomic structure in three dimensions makes it evident that there is an extended three-dimensional ‘tunnel structure’ between the octahedra, and these ‘tunnels’ are wide enough to permit facile transport of small ions in an electrical field. The most suitable ions are hydrogen ions (‘protons’, H^+) and lithium ions (Li^+). The nanoporous nature of the oxide – and therefore, the ease of ion transport – can be enhanced if it is prepared under conditions that make it strongly disordered on a scale that is larger than the one of the individual octahedra.

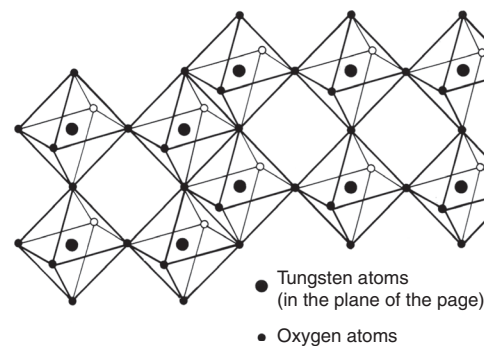
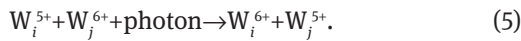


Figure 10 Schematic image of corner-sharing and edge-sharing octahedra in tungsten oxide. From Ref. [19].

The ion insertion into tungsten oxide is accompanied by an inflow of charge-balancing electrons from the electrodes in the electrochromic device. These electrons alter the valency of the tungsten atoms so that some of them are transformed from W^{6+} to W^{5+} . Now, consider a photon impinging on a tungsten oxide layer: this photon can have sufficient energy to transfer an electron between two neighboring tungsten ions (on sites i and j , say). The ensuing process is then, schematically,



This means that the photon energy is used to transfer an electron so that optical absorption takes place locally. The intensity of the overall absorption in the tungsten oxide, finally, is governed by the density of the inserted electrons, which in its turn is proportional to the amount of displaced ions.

Tungsten oxide is not the only oxide that darkens under charge *insertion*, and other alternatives are oxides of molybdenum, titanium, and niobium. Furthermore, there are other oxides that darken under charge *extraction*, such as nickel oxide and iridium oxide. Clearly, it is expedient to construct electrochromic devices so that they combine oxides of the two types, for example, tungsten oxide and nickel oxide, as transferring charge from nickel oxide into tungsten oxide darkens both of them, while transferring charge in the opposite direction bleaches both of them. This is the device design illustrated in Figure 9 above.

Figure 9 also shows how electrochromic glazings may be constructed in practice: one can start with two flexible plastic foils and coat them with two thin layers each; this can be performed by inexpensive roll-to-roll deposition. The thin oxide layers serving as anode and cathode are then connected by the polymer electrolyte, and finally, the entire electrochromic device is used as a laminate to join two glass panes, as indicated in the left-hand part of Figure 9. Another possibility that is currently being commercialized is to apply the full five-layer stack shown in Figure 9 directly onto the surface of a single glass pane by some advanced coating technology, which must guarantee that the anodes and cathodes are reliably separated. Figure 11 illustrates the transmittance modulation during the operation of a small electrochromic device, and Figure 12 shows a full-size installation of an electrochromic glazing.

Thermochromic glazings have been discussed for decades. The starting material is based on vanadium dioxide, which can be metallic and infrared reflecting well above room temperature and nonmetallic and infrared transparent below this temperature. A thin film

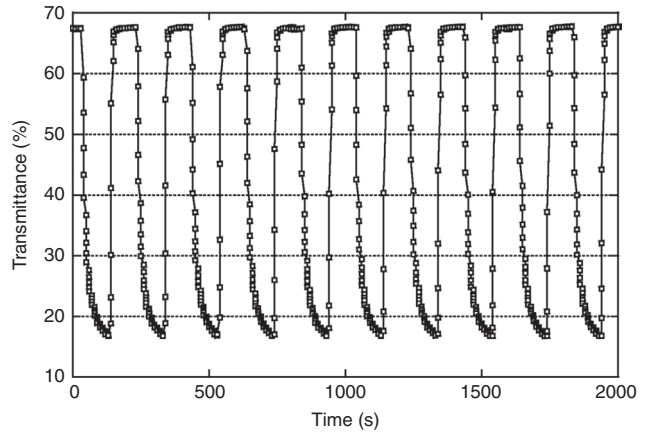


Figure 11 Modulation of the transmittance of visible light during repeated charging-discharging of a small electrochromic device of the kind shown in Figure 9.

of this material, therefore, transmits more solar energy when the temperature is low than when it is high, which is the desired property for energy-efficient fenestration. A problem, however, is that the transmittance modulation is low and significantly smaller than the one that can be achieved by electrochromism. However, as shown recently, vanadium dioxide-based nanoparticles seem to open new routes toward energy-efficient glazings [26]. Figure 13 indicates how such ‘nano-thermochromism’ may be implemented in a manner analogous to the one shown in Figure 9. Another forward-looking option might be to incorporate thermochromic nanoparticles in the electrolyte of the electrochromic device.



Figure 12 Part of an office equipped with electrochromic glazing, with one window being transparent and two windows in their dark state.

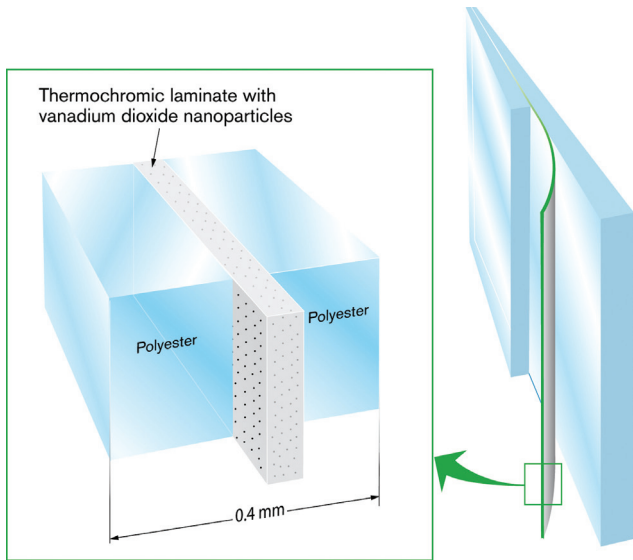


Figure 13 Construction principle for a foil incorporating thermochromic nanoparticles.

6 Comments and conclusions

The technological advances regarding optical coatings, referred to above, are not the only ones of interest for energy-efficient buildings. Other new developments concern photocatalytic coatings, usually based on titanium dioxide, on glazings. Ultraviolet solar irradiation activates these surfaces and allows them to disintegrate organic pollutants as well as cause almost complete wetting [1, 27]. Both of these effects contribute to making the surface easy to clean.

‘Low- E ’ coatings facing the air gap between glass panes improve the thermal insulation of glazings, as discussed above. Other measures to improve thermal insulation involve gas fillings, often with argon or krypton, which reduce heat conduction and convection. Even better thermal insulation can be accomplished with vacuum between the panes, which of course requires spacers to prevent implosion. Such spacers can be made from tiny glass pillars or from silica aerogel [28, 29]. The latter material comprises interconnected SiO_2 nanoparticles with sizes down to one nanometer; the overall porosity can exceed 99% so the weight is extremely small.

Improved thermal insulation is, of course, an asset, but it may have some (perhaps) unexpected side effects. Thus, if an extremely well-insulated glazing faces the clear night sky, it can experience cooling due to the imbalance between the outgoing radiation from the glass and the incoming radiation from the sky. This imbalance is connected to the ‘atmospheric window’ in the $8 < \lambda < 13\text{-}\mu\text{m}$

wavelength range, noted in Figure 1, which can cause a continuous heat loss as large as about 100 W/m^2 at ambient temperature and can lead to nighttime temperature decreases as large as about 10°C for surfaces that are freely exposed to the sky [30]. The net effect is that the glazing can reach a temperature below the dew point of the air, so that water condensation takes place. This phenomenon is well known for buildings in cold regions and typically occurs before sunrise. A good solution to this problem is to put a ‘low- E ’ coating on the outermost surface of the glazing, as was demonstrated for car windcreens many years ago [31]. Another solution is to have a superhydrophilic surface on the glazing, which tends to make liquid water invisible. Figure 14 shows the striking effect of a superhydrophilic titanium dioxide coating on the outer surface of a window [1].

We finally note, again, that the building sector consumes more energy than any other sector in the society. This is largely an effect of poor – but well-entrenched – building practices. There are many ways to radically diminish the energy expenditure, and building envelopes that function in harmony with the nature’s normal energy flows is a key. This involves spectrally selective surfaces, which reflect, transmit, absorb, and emit controlled amounts of energy in well-defined wavelength ranges, and further improvements can be achieved with chromogenic materials, which are able to alter the properties of the building envelope to compensate for varying temperatures, solar radiation flows, and lighting levels. Importantly, the changes can be implemented while the indoor comfort is improved.



Figure 14 Photograph of a window on a private house in Uppsala, Sweden. Both parts of the window are triple glazed and have a center-of-glass thermal conductance as small as $0.65\text{ W/m}^2/\text{K}$. The window is in a northeast-facing facade with an open view toward the sky. The left-hand part of the window has an outer glass with a self-cleaning and superhydrophilic TiO_2 -based coating, and the right-hand part employs standard uncoated glass. From Ref. [1].

The developments of buildings that presently are in progress may have far-reaching implications and involve a paradigm shift: thus, future buildings can serve as dynamic entities that adapt and adjust to varying demands, rather than being the static blocks of concrete, glass, wood, etc., of today. Another line of development can lead to light-weight climate shells surrounding buildings and blurring

the zone between indoors and outdoors. None of these changes will be rapid, however, and the time scale for introducing new and benign building technologies concerns decades.

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