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Energy-Efficient Optical Coating for Flat Glass

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Abstract: In this study, the recent trends for optical coatings in glass industries have been explored for the variety of climate dependent applications. Different coated glazings have been presented with their optical and thermal characteristics. A comparative analysis among types of coated products is also performed. It has been observed that for warm climate it is necessary to block near infra red portion of sunlight to reduce solar heat gain through windows. On the other hand, for cold climate it is necessary to allow the whole portion of light and it is necessary to block the IR radiation from escaping out to keep the interior space warm. For this purpose, Ag or Ag-alloy metallic thin film meet the requirements but they reduce visible transmittance as well. So for increasing visible transmittance, a dielectric layer of high refractive index is required. Here a variety of dielectric layers are studied. Finally for reaching the goal of low energy buildings in both warm and cold climates, appropriate optical coatings for architectural flat glass have been recommended.

Key words: Solar radiation, infra red (IR), nano-coating, solar control coating, low-emittance coating and energy savings

INTRODUCTION

The world wide relentless trend to decrease energy consumption necessitates variety of energy saving measures for the future green world. The high consumption of energy for cooling buildings as well as its resulting increase of CO_2 emission in Malaysia is also posing a threat to environment. It also drives architects, energy experts to emphasize more on climate responsive buildings, especially the facades and the right selection of glass/glazing to produce low-energy architecture. Solar energy is an inexhaustible energy source reaching earth in the form of electromagnetic waves. Glazed openings ranging from typical windows to large glazed building surfaces have become a common feature in architecture, allowing natural light into the building. From Fig. 1, it is obvious that a great portion of solar energy passes through windows directly or indirectly resulting in solar heat gain for building envelope.

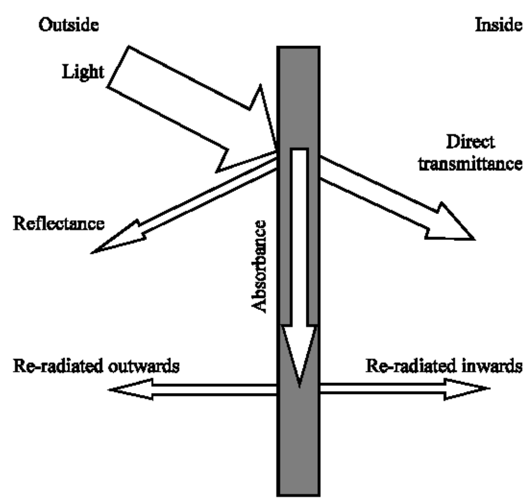

Fig. 1: Distribution of sun light through a single glazing

According to the Leadership in Energy and Environmental Design (LEED), one of the most prominently recognized architectural standards in green or sustainable building design, glass selection becomes a main element in this equation to contribute towards achieving a green building (Aboulnaga, 2006). Over the past 40 years, the introduction and development of the use of thin film coatings to enhance the thermal performance of window glazings and to exhibit a new dimension in the aesthetic aspects of building design has occurred. Previously, the glass manufacturers had made significant advances to improve the thermal performance through the development of sealed insulating glass and tinted or heat absorbing glasses. But there were practical limitations in these developments and serious thought began to be given in the 1950s to the possibilities of using coatings for additional performance enhancement. Introductory installations of coated glass began in the 1960s with the development of large-scale coating facilities and these were expanded considerably over the last two decades as the merits of coatings began to be appreciated (Berning, 1983).

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The key performance parameters for any energy efficient fenestration product are the Solar Heat Gain Coefficient (SHGC), the heat transfer coefficient (U-value) and the visible light transmission (T_{vis}). The U-value is a measure of the insulating value of a window; the lower the value, the better the insulation. SHGC is the ratio of the solar heat gain through the window system relative to the incident solar radiation and T_{vis} is weighted for human eye sensitivity. Reflected color and haze are equally important aesthetic properties. In cooling-dominated climates, solar heat gain is the most important parameter. The lower the SHGC, the lower the amount of solar heat transmitted through the window and thus the lower the cooling costs. The U-value is then of secondary importance. In heating-dominated climates, the window U-value is of primary importance. The lower the U-value, the better the insulation value. Solar heat gain is a secondary benefit. Most first generation fenestration energy codes focused on heating dominated climates, where a low U-value product was specified. Today, new codes and standards are in place or under developments which take into account the needs of cooling-dominated climates as well as areas where both heating and cooling are important. One such example is the Energy Star window-labeling program of the US Department of Energy which sets both U-value and SHGC standards climate zones of the United States. Although there are no standards for visible transmission, reflected color and haze, the existing low emissivity products on the market have high transmission values >70% and little or no reflected color (Russo *et al*., 2001). New energy-efficient products will have to meet or exceed these properties as well.

In warm climates, an energy-efficient glass window should have spectrally selective coatings such that it transmits nearly all the energy in the visible and reflects all the energy in the infrared. Thus an ideal energy-efficient window for a warm climate would have Transmittance (T) and Reflectance (R) to be given by: T = 1 and R = 0 for wavelength 400-700 nm (i.e., visible region) and T = 0 and R = 1 for wavelength >700 nm (infrared, IR, region) (Durrani *et al*., 2004). In other words, an energy-efficient window is a device capable of providing lighting and thermal comfort at minimum demand of paid energy. In a warm climate, when overheating from excessive solar input is a problem, one can obtain energy efficiency by using multilayer thin film-coated glass windows that are transparent for visible light and reflecting for IR solar radiation (Al-Shukri, 2007). The use of daylighting combined with high performance lighting through a energy-efficient glazing can lead to 30-50% savings and in some cases up to 70% (Wilson *et al*., 2002). On the other hand, for cold climates like Europe it is necessary to get optical coating on glass so that the glass can highly transmit sunlight in wide wavelength range (0.3 to 2.5 μm) and reflect the in-home heat radiation (2.5 to 30 μm) from warm bodies into the occupied space. The thermal transmittance (U-value) of window glazings must be less enough like below 2.1 W/m^{2}K. The requirement can be fulfilled by using double or triple glazings in combination with low-e coatings and inert gas filled in the space between the glazings.

In this study, an introduction to energy-efficient optical coating for residential and automotive purposes has been presented. We also cover some aspects related to science, technology and applications with focus on developments of coated flat glass.

OPTICAL COATINGS FOR ARCHITECTURAL FLAT GLASS

In on-line Chemical Vapour Deposition (CVD), multiple coatings less than a micron thick, to reflect visible and infrared wavelengths, can be deposited in the few seconds available as the glass ribbon flows beneath the coaters (British Glass, 2007). Since the end of the seventies vacuum coating technologies for the deposition of optical thin films on large area glass substrates have enjoyed a steady growth. The main applications today are found in the fields of so-called low-emittance coatings and solar control coatings or heat mirror films (Brauer, 1999). Electrochromic glazings are becoming an emerging technology as a viable option for dynamic control of solar energy and visible light. There are three main categories of energy-efficient window products on the market today pyrolytic low-E, Magnetron-Sputtered Vapor Deposition (MSVD) low-E and solar selective MSVD low-E (Russo *et al*., 2001). The pyrolytic and MSVD low-E products have low U values and are well suited to the heating-dominated climates. The MSVD low-E products also find wide use in the mixed heating and cooling regions because of their lower SHGC. The solar selective MSVD low-E products have the lowest SHGC and are best suited for the cooling dominated regions. However, MSVD products are far less durable and more reactive than their pyrolytic counterparts.

LOW-E COATING

Low-Emittance (Low-E) coatings are microscopically thin, virtually invisible, metal or metallic oxide layers deposited on a window or skylight glazing surface

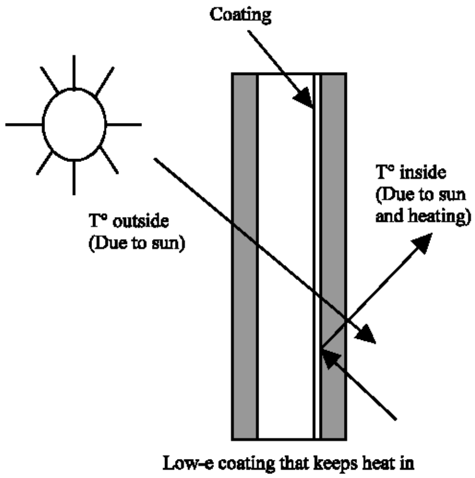

Fig. 2: Low-E coating for a double glazed window

primarily to reduce the U-factor by suppressing radiative heat flow as shown in Fig. 2. Coating a glass surface with a low-emittance material and facing that coating into the gap between the glass layers blocks a significant amount of the radiant heat transfer, thus lowering the total heat flow through the window. Different types of Low-E coatings have been designed to allow for high solar gain, moderate solar gain, or low solar gain (LBNL, 2007). High quality low-E coatings deposited by magnetron sputtering consist of ultra thin silver film between two transparent antireflective layers, typically metal oxides like SnO_2, ZnO, TiO_2. Today nearly all low emissivity glazings are based on a thin silver film. To maintain the high transparency of glass in the range of the visible spectrum and to protect the silver from corrosion, additional anti-reflective and protective layers of high refractive materials (e.g., SnO_2, ZnO, Si_3N_4, TiO_2) have to be employed (Brauer, 1999). Optical transmittance and reflectance spectra of the stacked-layers of TiO_2 and SnO_2: F showed good optical properties of high visible-light transmission and midrange infrared reflection (Leftheriotis *et al*., 1997). The U-value plays a significant role on saving heating energy in cold climates. The lower is the U-value, the lower is the heat loss. The U-value of glazings depends on the type of gas filling and the emissivity of the low emissivity coating. Also the least emissivity of the coating causes the heat radiation of warm bodies inside to reflect back into the heating space.

SOLAR CONTROL COATING

In solar control coating or in solar selective MSVD low-E, the highly reflective metal film that would otherwise be opaque to the visible light is sandwiched between the two dielectric layers that act as antireflective coatings. Three-layer systems of Dielectric/Metal/Dielectric (D/M/D) on glass substrates have been used for spectrally selective coatings for various purposes including the energy efficiency. By varying the material and thickness of the three layers, the optical properties of the D/M/D films can be tailored to suit different applications. The D/M/D films on a glass substrate were used as a spectrally selective filter that reflects infrared radiation (due to the properties of the metal layer) and transmits most of the visible spectrum (due to the properties of the dielectric layers) (Durrani *et al*., 2004). A thin silver material layer is mostly used as a reflective metal film and two same or different dielectric materials TiO_2, WO_3 and ZnS as layers were found to suit the optimized D/M/D films. A typical basic combination used earlier on was TiO_2/Ag/TiO_2 but commercial variations gradually evolved. First two pairs of tri-layers, later on an additional thin metal and silicon nitride were put to use replacing some silver and tin oxide was used instead of TiO_2. These glazings were proved to be very good in terms of performance, resulting in light gain and a reduction in solar heat (Smith *et al*., 2001).

To improve the glazing performance very thin (less than 2 nm) Cu block layers are used and it also protects silver against oxidation. Solar control coatings comprising TiO_2 and MgF_2 films, in which the silver layer beside MgF_2 (with thickness more than 10 nm) is not surrounded by oxide layers, have transmittance which is higher than 75% in the visible region and less than 10% at wavelengths longer than 1000 nm (Fu *et al*., 1997). Windows with a single Cu_2O film blocked only 50% of the near infrared. It was necessary to improve such windows by adding a second film of CuS yielding excellent results (NIR transmittance below 30%). A third kind of film was produced (Cu/Cu_2O) with high visible transmittance of 50% and good NIR selectivity. Thus copper composite based films are suitable for use as energy-efficient glazings in residential and commercial buildings (Correa and Almanza, 2004). The summarized multilayer combinations have been shown in Table 1.

Table 1: Typical multilayer energy-efficient optical coating

Low-E Multilayer coatings for cold climates	Low-E Multilayer coatings for cold climates
F: SnO_2	TiO_2/Ag/TiO_2
Sb: SnO_2	TiO_2/Ag/TiO_2/Ag/TiO_2
TiO_2/Ag/TiO_2	ZnS/Ag/ZnS
TiO_2/NiCr/Ag/NiCr/TiO_2	ZnS/Ag/ZnS/Ag/ZnS/Ag
TiO_2/Ag/Si_3N_4	Cu_2O/CuS
SnO_2/Ag/SnO_2	WO_3/Ag/WO_3
ITO/Ag/ITO	
ZnO/Ag/ZnO	
Al:ZnO/Ag/Al:ZnO	

ELECTROCHROMIC DEVICES

Electrochromics are a multi-layer coating on glass, about 1 μm thick, consisting of a purely ionic conductor (electrolyte) which is placed between electrochromic and counter electrode layers, which are, in turn, placed between transparent electrical conductor layers. When voltage is applied to the transparent conductors, an electrochemical reaction occurs in which ions are inserted or extracted from the electrochromic thin film, resulting in a modulation of optical properties (i.e., light and heat). Over the last few decades, a considerable interest remains in electrochromic materials, particularly in uses for windows and skylights to reduce building energy consumption (Lee and Dibartolomeo, 2002). In a electrochromic or switchable device, the most widely used tungsten oxide (WO_3) as an electrochromic films, V_2O_5 ion storage layers doped with lithium or Ta_2O_5 as an ionic conductor and silver-based multilayers like ZnS/Ag/ZnS or single layer like fluorine doped SnO_2 or indium doped SnO_2 (ITO) as a transparent electrode have been developed. Electrochromic devices could benefit from the reduced emittance and higher electronic conductivity of these multilayers (Papaefthimiou *et al*., 2001; O'Brien *et al*., 1999). Electrochromic devices are of interest for a wide range of applications and commercial activities (Fig. 3). In particular, energy-efficient windows with variable solar and luminous transmittance are able to reduce the influx of solar energy into a building. This will lead to large reductions in the need for cooling and air conditioning in warm and temperate climates. exhibit the following characteristics: (1) solar control properties that provide significant energy benefits and eliminate glare, (2) capability for high volume, in-line manufacture at a competitive price and (3) durability over a broad range of use conditions. A lithium based, thin-film system meets the requirements for architectural applications (Sbar *et al*., 1999).

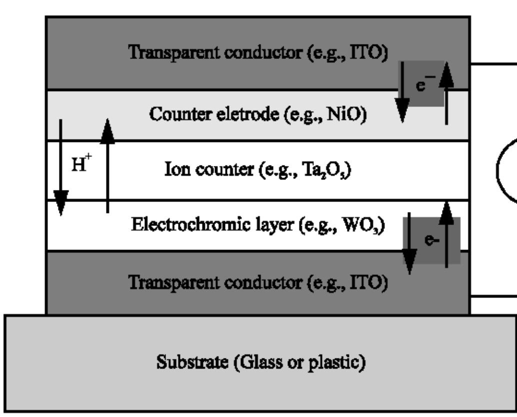

Fig. 3: A schematic of a typical electrochromic device

OPTICAL COATINGS FOR AUTOMOTIVE APPLICATIONS

The markets of vehicle manufacturing in South America, Eastern Europe and Asia except Japan are expected to grow tremendously. The coating technology is also expected to grow with this market growth. In the markets of North America, Western Europe and Japan, vehicle production cannot be expected to grow as much but the increase of house income will increase the adapting ratio of high performance windows on the vehicle. The production of coated glass for automotive applications can be said to be expected to increase. Low-emissivity coating is an optimum option for a single glazed window for vehicles. Generally speaking, visible transmittance of windows needs to be more than 70%. On the other hand, about 70% of solar energy inflow into room is through the windows. Therefore, high selectivity of visible transmittance to solar heat gain is needed for the crews' comfort. In this respect, sputter low-E glass is the best glass for automotive windows because of its high selectivity which was already mentioned earlier. Some parts of automobile windows do not need to have a high visible transmittance and low transmittance glass can be used for keeping the crews' privacy. These low transmittance glass are produced by a sputter coating of CrN and a spray pyrolysis one for Fe-Co-Ni-O coating.

COATING METHODS

A variety coating methods have been developed but when producing the coated materials with large area the available deposition methods are restricted to ones like chemical vapor deposition, spray pyrolysis, sputtering, sol-gel and vacuum vapor deposition. In this order, mass productivity decreases and flexibility becomes higher. Flexibility means the ease of making the changes in the deposition condition or deposited layer construction. Mass productivity is important for achieving the lower cost, but at the same time the flexibility is also important for improving the performance and matching the desired function of the product. The sputtering method is most commonly adapted on production lines because of its high mass productivity and high flexibility. The sputtering technique has made remarkable progress recently: for improving deposition rate by controlling the metal mode with measuring the plasma emission, with the use of rotatable cylindrical magnetron system, midfrequency AC dual magnetron sputtering and oxide-target sputtering (Schiller *et al*., 1987; Belkind *et al*., 1992; Szczyrbowski *et al*., 1997; Ohsaki *et al*., 2001; Brauer *et al*., 1997). These aggressive activities with sputtering technology are also one of the reasons why the sputtering has been the mainstream in the coating business. The commercially available optical coatings in different glass or relevant industries could be either pyrolytic (hard coat) or sputter coated (soft coat). Pyrolytic coatings are metallic oxides applied during the float manufacturing process. In soft coat, a thin, multi-layered piece of optically clear film is retrofitted to the inside surface of glass. It is sputter-coated with durable, exotic metals and their oxides such as titanium, copper, gold, silver, chromium, aluminium and other alloys. To meet the needs of the market for a durable, easily handled, energy-efficient glazing product for cooling dominated regions, ATOFINA embarked on a research program to develop a pyrolytic solar control low-E coating (Russo *et al*., 2001). The coating needed to have a SHGC low enough to meet the Energy Star requirement for windows used in cooling-dominated climates (<0.4), possess a high visible transmission, a low haze, utilize tin oxide or similar chemistry and be able to fit into current manufacturers' APCVD on-line processes.

ENVIRONMENTAL AND ENERGY ISSUES

Everyday, the world uses 320 billion kWh of energy. Energy consumption from fossil fuels has already generated CO_2 in 2002 of 2.6 billion tons/year and it is expected to increase in 2030 to 4.2 billion tons/year (Aboulnaga, 2007). According to US DOE Energy Efficiency and Renewable Energy (EERE) over 25% of the heating and cooling energy bills in a typical home are due to bad inefficient windows, door and skylights and namely to the type of glass used (Anonymous, 2008). Glass is a crucial element in the home energy efficiency battle. Clear single glass is highly inefficient and causes too much energy to be lost and too much sunlight to enter in homes when unwanted. Insulation of buildings is a key factor in energy efficiency, as the buildings account for a large portion of the total energy consumption in countries like Malaysia. Glass serves as one of the most viable solutions to provide energy savings in buildings with continuously developed new products ensuring heat insulation and solar control with increasing efficiencies and thus contribute to the net reduction in CO_2 emissions. High performance glasses contributing to energy conservation and environmental protection are developed by combining excellent properties of glass with enhanced coating technologies. Windows are typically the weak barrier from the thermal point of view, between the internal and external ambients. In cold climates, they are responsible for 10-25% of the heat loss from heated inner space to cold ambients (Ismail and Henriquez, 2003). In hot climates, the excess of solar radiation penetrating through windows increases cooling loads. An efficient way of reducing the cooling load in hot climates is to minimize the solar heat gain through glass windows. In cold climates it is necessary to increase the fraction of solar radiation entering into the heating envelope and to block the home heat radiation through glass window. Frequently windows are fitted with single clear glass sheet which results in being a weak barrier for heat flow due to incident solar radiation. This arrangement usually leads to radiation transmission of the order of 90% which is absorbed by the internal ambient and converted into heat. Additionally the standard glass sheets do not offer much resistance to heat flow by conduction and consequently provoke big thermal gain in hot climates. From Table 2, it is clear that there is a great potential for energy savings through the improvement of glazing performance as households, commercial buildings and transport have a great potential for energy savings.

The use of energy efficient windows is steadily increasing in Europe, although many new buildings are still equipped with uncoated standard windows. This is unfortunate since for every standard uncoated window fitted in new production, large amounts of energy will be wasted during the lifetime of this window. This fact is also pointed out in a report from GEPVP recently named as Glass for Europe-Europe's Manufacturers of Building, Automotive and Transport Glass where it is claimed that 1.1 million giga joules of energy would be saved every year if all single and double glazed uncoated windows in Europe were replaced by energy efficient coated windows. If all monolithic and double glazed units were replaced with low e coated double glazed units in EU countries, 82.41 million tons of CO_2 emission shall be avoided (GEPVP, 2005). Replacement of standard windows with windows of high optical and thermal quality such as double glazing with Low-e coating can reduce 20% heating and cooling requirements (Wenzel, 2007). In the

Table 2: Estimates for full energy saving potential in the end-use sectors

Sector	Energy consumption (Mtoe) 2005	Energy consumption (Mtoe) 2020 (Business as usual)	Energy saving potential 2020 (Mtoe)	Full energy saving potential 2020 (%)
Households (Residential)	280	338	91	27%
Commercial buildings (Tertiary)	157	211	63	30%
Transport	332	405	105	26%
Manufacturing industry	297	382	95	25%

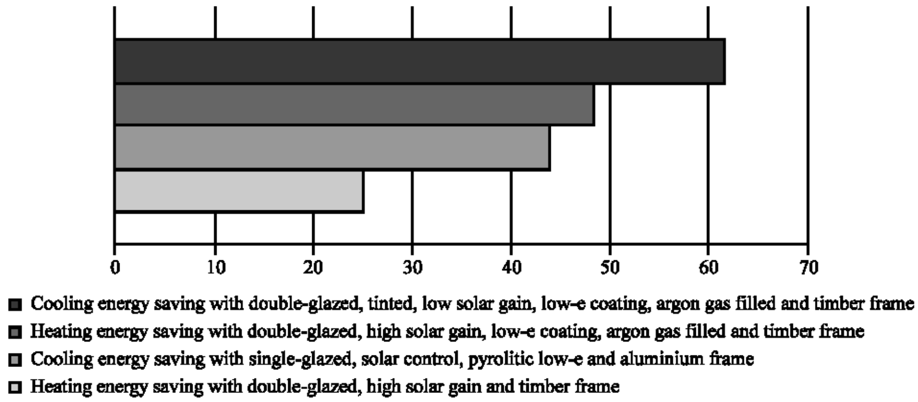

Fig. 4: Energy saving comparison between single and double glazed windows

hunt for low U-values, many combinations of glazings have been suggested and sometimes super windows with triple panes and two low-e coatings are proposed. Sometimes such a combination leads to a light transmittance which is lower than what is desired. By applying this switchable glass to windows in homes, offices and cars, the scientists estimate that reduced air conditioning needs could result in an energy savings of up to 30% (Physorg.com, 2007). These are climates where houses use more than 70 percent of their total space-conditioning energy for cooling. Warm humid and hot dry (tropical, subtropical and hot arid) climates are called cooling climates Cooling climates include tropical, subtropical and hot arid areas. Although the first two are frequently humid and the last is not, all three climates can subject a home to overheating at any time of the year. Overall glazing performance is dependent on a combination of passive design features as well as the performance of the glass (Anonymous, 2008).

Figure 4 shows the savings of home cooling energy in cooling climates for four window types, compared with using typical clear, single-glazed aluminium-frame windows and also shows that double-glazed windows with a high performance external tint, a low-e coating, an argon gas fill and an aluminium frame can reduce cooling energy requirements by almost 70% (Anonymous, 2008).

CONCLUSION

Deposition methods for large area coatings have been summarized from a production viewpoint. The sputtering method is adapted most commonly on production lines because of its high mass productivity, high flexibility and high R and D activities. Other methods, CVD, spray pyrolysis and sol-gel depositions have been applied using their advantages to give some products and are expected to be used more widely with the technological progress. The trends of architectural and automotive applications on the coating business have been discussed. On architectural and automotive applications, low-E glass is the most promising product and especially a Ag oxide stack low-E is expected to grow continuously. A large selectivity of visible transmittance to solar energy gain can be achieved by using an oxide or sulfide with high refractive index, like TiO_2, ZnS etc. TiO_2 has a low deposition rate when using a conventional sputter method and new high deposition rate sputter techniques have been already developed.

Low-E coating glass and spectrally selective solar low-E glass (also called *s*olar control glass) are the most common types of glass for boosting the energy efficiency of windows, glazed doors and skylights. In cold and temperate climates you should look for windows, doors and skylights with a low emissivity glass, capable of limiting as much as possible energy losses. To obtain that, the low-E double (or triple) pane, used in conjunction with gases (argon, krypton, carbon dioxide) filling the spaces between panes, is the ideal; low-E (low-emissivity) coating highly reduces heat loss through the windows, skylights and glazed doors. In hot climates, where cooling costs are higher than heating costs, one should look for windows, doors and skylights with a low SHGC 0.4 or less. To obtain that, solar control glass (also called spectrally selective solar Low-E and glass) is the best option. This glass is a good insulator and is the best on limiting solar heat gains due to its capacity of blocking infrared and some ultraviolet rays. Replacement of standard windows with energy efficient optical coating glass windows can reduce 20-30% heating and cooling requirements. Darker tinted glazing is a good option to provide lower solar heat gains, but it isn't as efficient as solar control glass and yield a decreased outdoor visibility, particularly at night. It can be concluded that the energy-efficient optical coating provides window glass with marketability value, Energy efficiency performance, Less emissions, adequate daylighting and good distribution and less glare.

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