Renewable and Sustainable Energy Reviews 26 (2013) 353–364

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Performance, materials and coating technologies of thermochromic thin films on smart windows

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ARTICLE INFO

Article history:
Received 6 December 2011
Received in revised form
5 May 2013
Accepted 20 May 2013
Available online 25 June 2013

Keywords:
Smart windows
Thermochromic glazing
Thin film
Nano particle
Glass coating

ABSTRACT

A significant amount of energy is consumed to maintain thermal comfort in buildings, a huge portion of which is lost through windows. Smart coating, thin films with spectrally selective properties on the surface of glass, is the innovative solution to the problem. Thermochromic smart windows change their color and optical properties in response to temperature variations. The performance, materials, coating technologies and energy modeling of thermochromic windows are reviewed in the present study. The effect of doping vanadium dioxide (VO_2) coatings with different dopants such as tungsten, fluorine, gold nanoparticles and etc. is elaborated. Various deposition techniques, specifically hybrid chemical vapor deposition (AA/APCVD) and physical vapor deposition (PVD) methods are elucidated. Different dopants and techniques show different results on metal to semiconductor transition (MST) and the critical temperature. The "change in visible and infra-red transmission and reflectance" is the touchstone of performance for the different afforded chromogenic intelligent windows.

Contents

1. Introduction

A significant amount of energy is consumed for maintaining thermal comfort in buildings. The energy used to maintain thermal comfort in buildings is mostly exploited to keep HVAC devices running. The building energy consumption in developed countries accounts for 20–40% of the total energy use. About 41% of primary energy the U.S. (as the second largest consumer of world energy representing 19% of global consumption), consumed in 2010 was for buildings sector. Consequently, this amount accounted for 7% of global energy use in 2010. Approximately 60% of all used energy in building sector was consumed for space heating, space cooling, lighting and ventilation in 2010 [1]. Buildings in China, as the largest consumer of world energy, consumed 26% of total primary energy in 2006; the figure is anticipated to rise to more than 30% by 2020 [2]. The building energy consumption is even more dominant in hot and humid regions, using one-third to half of the electricity produced in some countries [3–5].

In addition, building sector was the culprit of around 40%, 18% and 8% of energy-related carbon dioxide emissions in 2010 for the US, China and worldwide, respectively [1,6]. Therefore, energy saving measures should be taken in order to reduce buildings energy losses and CO_2 emissions.

There are two approaches in building energy saving strategies, the active strategies and the passive ones. Improving HVAC

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.05.038

Nomenclature

TC	Thermochromic
EC	Electrochromic
TCW	Thermochromic window
ECW	Electrochromic window
SPD	Suspended particle device
MST	Metal to semiconductor transition
ΔT	Change in transmittance
T_t	Transition temperature (critical temperature)
PVD	Physical vapor deposition
CVD	Chemical vapor deposition
APCVD	Atmospheric pressure chemical vapor deposition
AACVD	Aerosol assisted chemical vapor deposition
ΔR	Change in reflectance

systems and building lighting can actively increase the building's energy efficiency, whereas measures amending the properties and thermal performance of building envelopes such as adding thermal insulation to wall, using cool coatings on roofs and coated window glazing are among the passive methods. Any building element, such as wall, roof and fenestration which separates the indoor from outdoor is called building envelope [7–10].

Windows are known as one of the most energy inefficient components of buildings [11]. Preventing these losses by improving the windows thermal performance will result in reduced electricity costs and less greenhouse gas emissions. While controlling transmitted Infrared (IR) radiation, an ideal window should be capable of sufficient transmission of visible light [12]. The most significant parameters influencing the heat transfer through windows include outdoor conditions, shading, building orientation, type and area of window, glass properties and glazing characteristics [13]. Improving glazing characteristics of windows such as thermal transmittance and solar parameters is the most important criterion to be considered in building windows standards [14]. Several international standards have been published to evaluate the performance of windows and glasses in building in order to achieve minimum requirement by considering energy performance improvement of building. ISO 10291:1994 [15], ISO 12567:2005 [16,17], ISO 9050:2003 [18], and ISO 14438:2002 [19] are the examples of such standards.

Based on international standard (ISO 9050) [18], light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors are the essential parameters for determining the light and energy performance of glazing in building. Some studies have been done based on this standard (or its European equivalent EN 410) [20] in order to determine the optical properties of coated glass products [21], modeling the solar energy transmittance of windows by considering to the angular behavior, and calculate the solar control parameters [22].

Generally, international standards specify the criteria and the essential characteristics to be considered worldwide. International standards can apply directly or modify based on the local conditions. There are many international and local standards related to the energy and lighting performance of windows, some of which are tabulated in Table 1.

The thermal dynamics and lighting potential of glazing should be considered in building energy calculations. Energy efficiency in building envelopes is generally calculated based on the ratio of the temperature difference across a building compartment and the heat flux (R-value) or the rate of heat transfer through a building element at certain conditions (U-factor). In cold climates, low U-factors or high R-values prevent heat from escaping from buildings, and in hot climates, they prevent heat from entering buildings [23,24].

2. Smart windows

Smart windows, defined as the type of windows that partially block the unwanted solar radiation, can help building to maintain higher energy performance levels. The energy performance can be improved by increasing heat gain in cold weather and decreasing it in hot weather by adopting windows' radiative and thermal properties dynamically [25]. Adding controllable absorbing layer on the surface of the glass can change the optical properties of the glass by controlling the incident solar heat flux [26]. Therefore, smart windows lead to reduced HVAC energy consumption and size and electric demand of the building [11,27,28].

There is a wide range of modern intelligent glazing options for energy saving purposes including Low-e coatings [29,30], micro blinds, dielectric/metal/dielectric (D/M/D) films [31,32], and switchable reflective devices including electrochromic windows (ECW) [33–35], gasochromic windows [36], liquid crystal glazing [11], Suspended-Particle Devices (SPD) [37] and thermochromic windows (TCW).

Low emissivity (low-E) coatings are spectrally selective films that are aimed to let the visible light pass through and block the IR and UV wavelengths which generally create heat [10]. Because of its high IR-reflectance, this type of glazing has been developed greatly, and many have studied their different properties during the last two decades [30,38–40]. Typically, there are two types of low-e coatings, the tin oxide based hard coating and the silver based soft coating with higher IR reflectance and lower transmittance than the other one. However, the visible transmittance of hard coatings can boost up with anti-reflecting property of silicon dioxide [29].

D/M/D films on glass exhibit great energy saving effects by reflecting the IR radiation by their reflective metal film and transmitting visible and near IR radiation through the two antireflective dielectric coatings [41]. Design, fabrication and properties of D/M/D films have been studied thoroughly by many researchers focusing on the optimization [31,32,42–45]. Beside the optimized performance, cost of these films in terms of their material and the fabrication technique is also important [41].

The switchable reflective devices (also called dynamic tintable windows) are categorized in to passive and active systems. In passive devices, the switching process is activated automatically in accordance with the environmental conditions. This environmental factor can be light in case of photochromic windows; or temperature and heat in thermochromic windows (TCW). Alternatively, the active systems require an external triggering mechanism to perform the modulation. For instance, electricity is the actuating signal in electrochromic windows (ECW). The active switchable glazing systems offer supplementary options compared to the passive systems whereas their dependency on power supply and wiring should be reckoned with as a drawback. Chromic materials, liquid crystals, and suspended particle windows are the three most common active-controlled intelligent windows [11]. The latter two share the disadvantage of their dependency on an electric field to be maintained when a transparent mode is desired; resulting in excessive electricity consumption. This is not the case in EC glazing that wants electricity only for transition [46]. However, chromic materials are classified into four types: electrochromic (EC), gasochromic, photochromic and thermochromic (TC). The first two belong to active glazing, responding to electricity and hydrogen