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Sol-gel approaches to thermochromic vanadium dioxide coating for smart glazing application

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ABSTRACT

Thermochromic VO_2 has received great attention for smart window application because of its ability to control solar heat gain in response to the temperature variations. It goes through a first order reversible phase transition from the semiconductor to metallic state at critical temperature of 68 °C, having higher infrared reflectance above this temperature. This paper summarizes some prominent theories behind this phase transition and presents a comprehensive review of recent progress in all-solution synthesis of VO_2 thin film with a particular focus on sol-gel method. Emphasis is given to highlight different precursors exploited to prepare thin films with adjustable morphology and optimized optical properties. Actually, VO_2-based coatings show good combination of integrated luminous transmittance (33.1–81.3%) and solar modulation ability (2.2–22.3%). The effect of various dopants such as tungsten, magnesium on thermochromic properties of VO_2 thin films is also elaborated. These studies indicate that innovative solutions are essential to overcome the current shortcomings associated with practical application of VO_2.

1. Introduction

Increasing global energy demand raises many environmental problems, which have brought great attention into the energy preservation strategies in many countries. The building sector, as one of the huge energy consumers, is recognized to account for 40% of the overall energy consumption in the world [1]. The increment in energy consumption could be the result of modern urbanization and propensity to obtain better quality of life. Thus, mitigation measures, as issued in EU directive (2010/31/EU), should come into force to reach the zero-energy building in next few years [2]. Various options are theoretically available to reduce the use of conventional energy, whilst still meeting global energy demands. One solution is to use renewable sources, however, regardless of the technical breakthroughs, implementation of renewable energy systems is often unfeasible and subject to high level of intermittency [3]. It is unlikely that any single source will be able to adequately supply the level of energy required.

On the other hand, energy saving has been identified as an alternative to resolve the above problems. It is generally cost effective and has the same level of advantages compared to renewable energy systems toward decreasing total energy consumption [4]. Energy in buildings is mainly consumed for heating, air conditioning, ventilation and lighting [5]. Among all the building envelopes, windows are responsible for 40% of the total energy losses from buildings [6,7]. However, windows cannot be eliminated because they allow natural light into the building, which provides certain biological advantages [8]. Nevertheless, a significant energy saving is possible, if windows were able to alter their rate of transparency to the solar irradiance [9]. In this context, advanced window technologies have been proved to be more useful than the classical approaches like blinds, as they are able to reduce lighting and cooling loads in warm climates by 26% and 20%, respectively [5].

There is a considerable amount of literature on static solar control systems, such as low-Emissivity glazing, solar control glazes, multi pane windows, vacuum glazing and more recently transparent photovoltaic (PV) facades. They have been employed to improve optical and thermal properties of the building fenestration [10]. Each of the aforementioned technologies has their own distinctive advantages. For instance, multi pane windows have high U-values; PV glazings are favorable due to the potential of supplying electricity and thermal comfort simultaneously; and in contrast to low-Emissivity windows, vacuum glazing are able to decrease building energy consumption regardless of window orientation [5]. However, application of static windows is limited to the regions where climate is consistently warm or cold [11].

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More recently, a promising class of technologies for dynamic control of solar energy set the technology bar even higher, including chromogenic, liquid crystal (LCD) and suspended particle devices (SPD) [12]. These so-called smart windows are able to reversibly adjust daylighting and solar heat gain in response to external stimulus [13]. Despite favorable progress in optical properties of LCD and SPD technologies, further discussion is out of the scope of this study, but a comprehensive investigation can be found elsewhere [12].

Chromogenic materials have received great attention over the few past decades. In general, these materials are categorized as electrochromic, gasochromic, thermochromic and photochromic, which their optical properties depend on an applied voltage, gas exchange process, ambient temperature and ultraviolet light intensity, correspondingly. Among all the chromogenic material, electrochromic windows seem to have the most promising energy saving performance [14]. In spite of its advantages, large scale manufacturing of electrochromic windows faces several challenges, including complicated multilayer structure, long term durability, efficient charge insertion and suitable electrolyte with high ultraviolet stability and ion conductivity [15]. On the other hand, gasochromic windows are simpler and economical compared to electrochromic windows as stacking of transparent conducting layers is no longer required [12]. In addition, gasochromic windows could significantly reduce yearly HVAC consumption by 25–35% [13]. However, the key problems with much of the literature regarding application of gasochromic windows are limited switching cycles and use of redox gases. Thermochromic windows are among the most commonly investigated types of chromogenic materials. In this regard, this paper aims to outline the recent progress in sol-gel and solution derived vanadium dioxide (VO_2) thin films and may provide considerable insight to better understanding the correlation between film structure and phase transition properties.

2. Thermochromic window

The generally accepted use of the term thermochromism refers to the ability of a material in changing the electro-optical properties as a function of temperature [16]. Fig. 1 shows that thermochromic windows selectively adjust the infrared (IR) transmittance across a critical point known as transition temperature (T_t). Therefore, the amount of heating energy from the incident light changes significantly in response to the ambient temperature.

Although thermochromic windows are theoretically not as effective as the electrochromic ones in energy saving features, they have an uncomplicated structure and this is a considerable advantage. The candidate glazing should demonstrate a set of special properties in order to be practical for the energy-efficient glazing systems. With regard to the primary aim of building fenestrations, thermochromic thin films should have high transparency in the visible spectrum to let sunlight reaches inside the building to reduce lighting loads. Furthermore, their optical characteristics should largely change in the IR region, particularly having higher reflectance value over IR range in order to modulate solar heat gain. Finally, is the transition temperature, which is required to be close to the room temperature [18].

VO_2 has received great attention for smart window application because of its ability to control solar heat gain [19]. Owing to its distinctive properties, VO_2 also offers potential for other technological uses, including IR bolometers [20,21], gas sensor [22,23], optical data storage and optical switching systems [24–26], flat panel display [27], electrode material in lithium batteries [28–30], and more recently in the terahertz range applications [31,32].

3. Vanadium dioxide

Vanadium presents a partly-filled 3d orbital, leading to form several oxides such as VO, V_2O_3, V_4O_7, VO_2, V_2O_5 and V_6O_{13}, which all belong to the series of Magneli (V_nO_{2n-1}) and Wadsley ($V_{2n}O_{5n-2}$) systems [33]. Among all, VO_2 has been greatly studied since it goes through a first order reversible phase transition from the semiconductor to metallic state (MST) at critical temperature of 68 °C [34]. This transition leads to abrupt changes in electro-optical properties of VO_2 [35], which takes place rapidly in 10^{-12} s [36,37]. Throughout the transition, atom displacements may cause the electronic charge in VO_2 crystal network to be redistributed, and consequently influence the nature of vanadium-oxygen system [33]. It should be noted that VO_2 crystals are inclined to shatter after a small number of phase changes. Thus, thin films structures are more of interest for practical applications because of their better endurance towards structural deformity [35]. However, when contrasted to VO_2 single crystals, thin films go through phase transition within an extended temperature range; and they exhibit less variation in their properties. These deviations might be associated with several factors, like defects or non-stoichiometry in crystals and dimensional impacts [38].

VO_2 has a rutile tetragonal structure (above T_t) with every vanadium atom connected to six adjacent oxygen atoms creating an octahedral shape. This structure is known as the metallic R-phase related to $P4_2/mnm$ space group with the lattice variables of

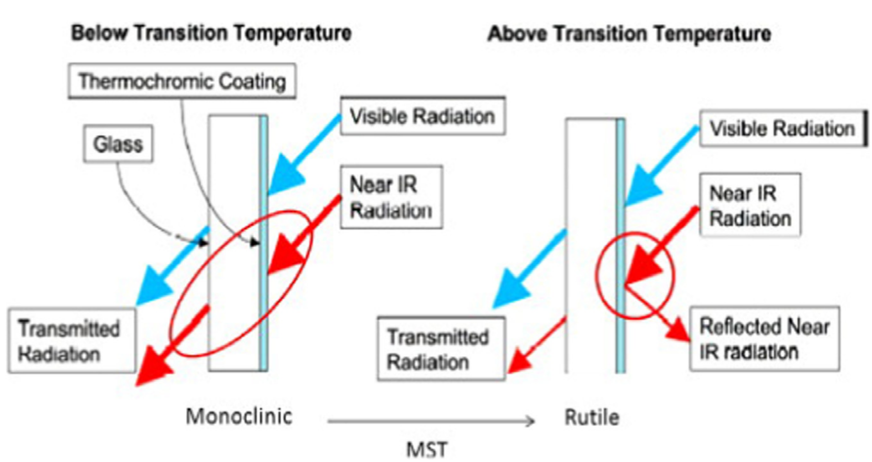

Fig. 1. Thermochromic window behaviour [17].