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A novel multifunctional thermochromic structure with skin comfort design for smart window application

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ABSTRACT

In this paper, we reported a VO_2-based thermochromic window using bistratal glasses of TiO_2 antireflection coating as well as Al: ZnO/SiO_2 coatings, respectively. The thermochromic behavior of VO_2 was modulated by TiO_2 antireflection layers based on skin comfort design for the first time. The film thickness of TiO_2(240 nm)/VO_2(70 nm)/TiO_2(10 nm)/Glass structure has been optimized based on modulation of 1350 ~ 2500 nm solar radiation by calculation. A remarkable improvement in mid-infrared reflectivity was obtained using Al: ZnO with SiO_2 layer, and the film thickness has been optimized as SiO_2 (~100 nm)/Al: ZnO (300 nm)/Glass to achieve a suitable integrated luminous transmittance. This two multilayered stacks were combined together with different orders to form a multifunctional window for energy efficient fenestration. This work provides a new insight for structural design of multilayer thin films and serves as starting points for developing novel coatings for windows with superior energy efficiency.

1. Introduction

Chromogenic materials are widely studied for future energy-saving project [1] and have great potential to decrease the amount of energy consumed in building environments. Smart materials, which are based on chromogenic materials, can sense and respond to external stimuli and spontaneously regulate energy passage [2–4]. The main chromogenic technologies include electrochromic (depending on electrical voltage or charge), thermochromic (depending on temperature), photochromic (depending on ultraviolet irradiation), and gasochromic (depending on exposure to reducing or oxidizing gases). Among of them, vanadium dioxide (VO_2) based thermochromic smart window has attracted considerable interest because of its various advantages such as simple structure, automatic control, and easy to mass production. VO_2 material undergoes a metal-semiconductor transition at the critical temperature (T_c) of 340 K, which is a first-order structural phase transition from a high temperature metallic rutile (R) phase to a low temperature semiconductor monoclinic (M) phase accompanied with abrupt changes in optical and electric properties [5,6].

In terms of practical applications, there are still some obstacles to overcome. First, the thermal emissivity of VO_2 is quite high which decreases the thermal insulating ability of the window, leading to high heat exchange and energy consumption [7–9]. Second, the fabrication of VO_2 films with good thermochromic performance requires high deposition temperature, usually over 400 °C, making it difficult to produce with the present industrial production lines [10–12]. Third, it has been difficult to achieve a sufficiently large transmittance and satisfied thermochromism at the same time [13,14]. These obstacles form the basis of the present work, wherein we systematically explore the possibilities of benefiting optical performance from multilayer stacks of the types $TiO_2/VO_2/TiO_2$ combined with SiO_2/Al doped ZnO(AZO). This paper reports some recent results on VO_2-based multilayer films and demonstrates that the luminous and solar transmittance can be optimized according to the design of the multilayer stack. The optical performance of the deposited window structure was characterized, and the detail was reported. Multilayered structures incorporating AZO and VO_2 [15,16] or VO_2 and TiO_2 [3,4,17] have been studied before, but we go beyond these previous work by looking at five-layer coatings, which will be demonstrated below, offer some specific advantages.

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2. Computational simulation and experiment

2.1. Computational simulation

The optical properties of the proposed window were studied theoretically using the transfer-matrix method, and the incoherence of the glass substrate was especially taken into account based on the idea of multiple reflections of field amplitudes [17–19]. The optical constants (n and k) of VO_2, TiO_2, SiO_2, AZO and quartz glass were used for calculation. The design and calculation method has been reported in our previous studies [3,17]. The integral luminous transmittance (T_{lum}) and integral solar transmittance (T_{sol}) were obtained from $T_{lum,\ sol}(\tau)=\int \varphi_{lum,\ sol}(\lambda)\times T(\lambda,\ \tau)d\lambda/\int \varphi_{lum,\ sol}(\lambda)d\lambda$, where φ_{lum} is the spectral sensitivity of the light-adapted eye and φ_{sol} is the solar irradiance spectrum with an air mass of 1.5 (corresponding to the sun being 37° above the horizon), $\triangle T_{sol}$ was obtained from $\triangle T_{sol} = T_{sol,l} - T_{sol,h}$, where l and h denote low-temperature (25 °C) and high-temperature (95 °C), respectively.

2.2. Preparation and characterization of thin films

All the thin films in the multilayered structures of SiO_2/AZO/Glass (SiO_2/AZO was written as SA for short) and $TiO_2/VO_2/TiO_2$/Glass ($TiO_2/VO_2/TiO_2$ was written as TVT for short) were obtained on 0.5 mm quartz glasses by means of magnetron sputtering apparatus (ULVAC Corp., Model ACS-4000-C4). Based on the calculations, the optimal film thickness of AZO and SiO_2 for SA/Glass was ~300 nm and ~100 nm, respectively. AZO and SiO_2 thin films were deposited by rf sputtering on one quartz glass in turn with AZO target (ZnO=98% by weight, Al_2O_3=2% by weight) and SiO_2 target, respectively. AZO thin film was obtained at the substrate temperature of ~ 250 °C during the deposition process, while the SiO_2 layer was prepared at room temperature. It has been reported that the least thickness of VO_2 to show significant thermochromic performance should be over 50 nm [13,14], thus 70 nm VO_2 thin film was chosen on the basis of optimization results. Therefore, the TiO_2/VO_2(70 nm)/TiO_2 films with optimal film thickness were deposited on another quartz glass in a versatile thin deposition system. VO_2 layer were obtained at the Ar/O_2 ratio of 14.3 and the pressure of 0.6 Pa, by reactive dc magnetron sputtering at the substrate temperature of 375 °C. TiO_2 layer was formed on the bottom and top of VO_2 at the substrate temperature of 375 °C, by reactive dc magnetron sputtering as well. Then these two glass stacks (SA/Glass and TVT/Glass) were combined together in different modes to form a smart window.

Film morphology and thicknesses were measured by scanning electron microscopy (SEM, HITACHI S-3400) and surface morphology by atomic force microscopy (AFM, SII Nano Technology Ltd, Nanonavi Π). The optical properties of the films were characterized by a UV–visible-NIR spectrophotometer (HITACHI UV4100) for visible–near infrared transmitting spectra (350 nm–2500 nm) and a Fourier Transform Infrared Spectrometer (FT-IR, NICOLET iS10) for mid-IR transmitting spectra (2.5–25 μm).

3. Results and discussion

The so-called smart window glass means glass with the adaptability of seasons. In winter, this kind of glass possesses high reflectivity in mid-infrared wavelength range (MIR, 2.5–25 μm) and high transmittance in near-infrared wavelength range (NIR, 780 nm~2.5 μm). In summer, smart window glass should own high reflectivity in the range of wavelength larger than 1 μm. At the same time, the transmittance in the visible range (380–780 nm) in both summer and winter should be in high value to maintain comfortable daylighting. To achieve these functions, it is necessary to combine low-emission film (Low-E) with thermochromic film, since that high MIR reflectivity equivalent to low-emission according to Kirchhoff's law: [10]

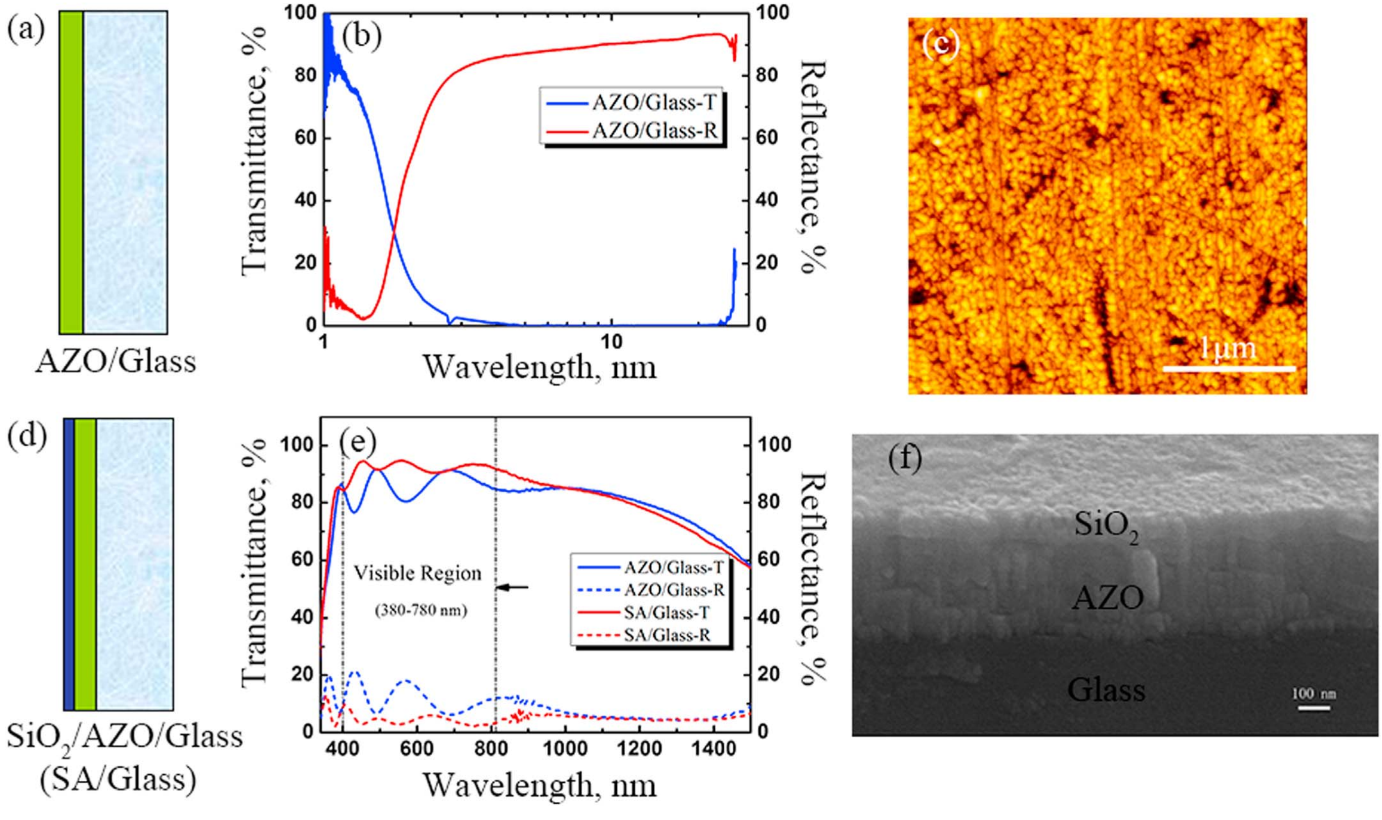

Fig. 1. Structure and performance of AZO/Glass and SA/Glass. (a) Schematic illustration of AZO/Glass; (b) MIR transmittance and reflectance spectra of AZO/Glass; (c) AFM image of surface morphology of SA/Glass; (d) Schematic illustration of SA/Glass; (e) Visible-NIR transmittance and reflectance spectra of AZO/Glass and SA/Glass; (f) Cross-sectional SEM image of SA/Glass.