1. Introduction

Following the Paris agreement, it has been established that the world must aim at reducing and limiting the Earth’s temperature increase to well below 2 °C above pre-industrialized levels [1]. While part of the solution may rely on changing our everyday habits, it has also become obvious that technology has the potential of significantly impacting the energy landscape. In fact, technology can be applied to reduce energy consumption, but can also positively impact our living environment which need to be addressed before its commercialization. Amongst these, its low luminous transmittance has been the subject of many studies. In the present work, we propose to integrate a VO₂ film into a traditional silver-containing low emissivity coating architecture. We first model and discuss the theoretical performance of such a coating in comparison with more standard configurations and demonstrate that the addition of silver offers many advantages for thin VO₂ coatings; mainly an increase of luminous transmittance due to the presence of antireflective coatings while maintaining a high solar transmittance variation vs. temperature. The latter is shown to be the result of a displacement of the maximum transmission variation to lower wavelengths where the solar intensity is higher. We then fabricate prototype samples which confirm the predicted performance. Indeed, a silver-containing sample based on the following architecture Si₃N₄ [57 nm] | VO₂ [27 nm] | Ag [11 nm] | Si₃N₄ [66 nm] is shown to possess the unique combination of a high luminous transmittance of 58.2% in its low temperature state, a solar transmittance variation of 7.1% with the added benefit of a low emissivity of 10%.

Vanadium dioxide is one of the likeliest candidates for future smart window applications due to its self-regulating nature and potentially simple implementation. However, the material is plagued with multiple drawbacks which need to be addressed before its commercialization. Amongst these, its low luminous transmittance has been the subject of many studies. In the present work, we propose to integrate a VO₂ film into a traditional silver-containing low emissivity coating architecture. We first model and discuss the theoretical performance of such a coating in comparison with more standard configurations and demonstrate that the addition of silver offers many advantages for thin VO₂ coatings; mainly an increase of luminous transmittance due to the presence of antireflective coatings while maintaining a high solar transmittance variation vs. temperature. The latter is shown to be the result of a displacement of the maximum transmission variation to lower wavelengths where the solar intensity is higher. We then fabricate prototype samples which confirm the predicted performance. Indeed, a silver-containing sample based on the following architecture Si₃N₄ [57 nm] | VO₂ [27 nm] | Ag [11 nm] | Si₃N₄ [66 nm] is shown to possess the unique combination of a high luminous transmittance of 58.2% in its low temperature state, a solar transmittance variation of 7.1% with the added benefit of a low emissivity of 10%.

1. Introduction

Following the Paris agreement, it has been established that the world must aim at reducing and limiting the Earth’s temperature increase to well below 2 °C above pre-industrialized levels [1]. While part of the solution may rely on changing our everyday habits, it has also become obvious that technology has the potential of significantly impacting the energy landscape. In fact, technology can be applied to reduce energy consumption, but can also positively impact our living environment which need to be addressed before its commercialization. Amongst these, its low luminous transmittance has been the subject of many studies. In the present work, we propose to integrate a VO₂ film into a traditional silver-containing low emissivity coating architecture. We first model and discuss the theoretical performance of such a coating in comparison with more standard configurations and demonstrate that the addition of silver offers many advantages for thin VO₂ coatings; mainly an increase of luminous transmittance due to the presence of antireflective coatings while maintaining a high solar transmittance variation vs. temperature. The latter is shown to be the result of a displacement of the maximum transmission variation to lower wavelengths where the solar intensity is higher. We then fabricate prototype samples which confirm the predicted performance. Indeed, a silver-containing sample based on the following architecture Si₃N₄ [57 nm] | VO₂ [27 nm] | Ag [11 nm] | Si₃N₄ [66 nm] is shown to possess the unique combination of a high luminous transmittance of 58.2% in its low temperature state, a solar transmittance variation of 7.1% with the added benefit of a low emissivity of 10%.
would pose quite a challenge. Another example by Saint-Gobain emphasizes the possibility of an adjustable solar transmittance as well as of applying a current on the silver film (or ITO) to control the VO2 film’s temperature; however, the silver-containing examples all display $\tau_{\text{lum}}$ values below 35% [25].

Silver being such an interesting material, other authors have also discussed its combination with VO2 in various applications such as active metamaterials [26], nonlinear optical switches with silver or gold covered VO2 nanoparticles [27], subwavelength hole arrays with variable transmittance [28], silver nanoparticles deposited onto VO2 with variable surface plasmon resonance or to tune the color and spectral properties of VO2 [29,30], temperature self-regulating core-shell nanoparticles [31] and tunable thermal emissivity [32].

The film architecture proposed here also benefits from low emissivity (low-e) properties. In fact, a low thermal emissivity and thus high IR reflectance is critical to ensure that the solar energy absorbed by the VO2 coating, which is then re-emitted through black body radiation in part towards the interior of the building, is rejected. The concept of combining therмochromism and low-e properties is not new and, for example, Kang et al. [33] proposed the addition of a top platinum film; the result was indeed a coating system with a lower emissivity (lowest obtained value of 56% in the low temperature state). Interestingly, they also added a top SiO2 antirefective coating to enhance $\tau_{\text{lum}}$, which nevertheless remained quite low ($T_{\tau_{\text{lum}}} = 37.9\%$). In a similar effect, silver nanowires have also added to the surface of VO2 to lower its emissivity (lowest value of 60.3%) [34]. An obvious alternative to metal films are transparent conductive oxides (TCO) and multiple examples of their implementation can be found in the literature. For example, VO2 films where grown over F:SnO2 films with results which are in line with the present study (13% emissivity) [35]. These polycrystalline TCO films were also shown to be beneficial for VO2 growth by enhancing crystallinity and lowering the deposition temperature.

Thus, in this work, we first model the impact of the addition of silver in combination with VO2 by comparing the thermochromatic performance of three model stacks, namely, a single VO2 film, an antireflection-based Si3N4|VO2|Si3N4 stack, and finally our proposed thermally active low-e Si3N4|VO2|Ag|Si3N4 architecture. We then demonstrate that with silver, the $\Delta T_{\text{sol}}$ can be maintained at higher levels for VO2 thicknesses below 80 nm. Follows an analysis of fabricated prototype samples which confirm our initial modeling results and which demonstrate a truly unique combination of performance indices for a thin VO2-based device (< 30 nm) resulting in a high luminous transmittance, a respectable solar variation, and a low emissivity.

2. Experimental methodology

2.1. Optical modeling

The theoretical optical performance of the studied architectures was performed by the implementation of the matrix formalism in Matlab [36]. Note that the backside reflection of the glass substrate was included during modeling. The results were additionally validated with OpenFilters [37]; the later was also used when modeling specific optimized architectures obtained using the Matlab program. The calculations were performed using the list of materials shown in Table 2. The silver properties [38] were extrapolated from 1938 nm to 2500 nm by using a Drude model implemented in the CompleteEase software from J.A. Woollam Co. Three specific architectures were studied:

- Standard: B270 | VO2
- Antireflective: B270 | Si3N4 | VO2 | Si3N4
- Low-e-based: B270 | Si3N4 | VO2 | Ag | Si3N4

Si3N4 films were chosen as the antireflective dielectric material for practical reasons as from a process point of view, it is simpler to sputter a nitride over silver without the use of a protective film; indeed, in the specific case of oxides a thin metal layer is typically added [40]. In addition, it is also a good diffusion barrier, which turns out to be critical when depositing VO2 onto glass at high temperatures [6]. The performance of the different architectures was assessed through the luminous transmittance $\tau_{\text{lum}}$ (at low temperature) and the solar transmission variation between the low and high temperature states, $\Delta T_{\text{sol}}$. Both these parameters were calculated using the following equations integrated at every 1 nm:

$$\Delta T_{\text{sol}} = T_{\text{high}} - T_{\text{low}},$$

where $T_{\text{high}}$ is the transmittance at high temperature and $T_{\text{low}}$ is the transmittance at low temperature.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness range [nm]</th>
<th>$n$ @ 550 nm</th>
<th>$k$ @ 550 nm</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>B270 substrate</td>
<td>2 nm</td>
<td>1.524</td>
<td>&lt; 10^-4</td>
<td>Measured [59]</td>
</tr>
<tr>
<td>Si3N4</td>
<td>0 – 200</td>
<td>2.037</td>
<td>6.9 x 10^-5</td>
<td>[40]</td>
</tr>
<tr>
<td>VO2</td>
<td>@ 21 °C</td>
<td>2.932</td>
<td>0.534</td>
<td>[14]</td>
</tr>
<tr>
<td>VO2</td>
<td>@ 90 °C</td>
<td>2.465</td>
<td>0.561</td>
<td>[14]</td>
</tr>
<tr>
<td>Ag</td>
<td>8</td>
<td>0.060</td>
<td>3.598</td>
<td>[38]</td>
</tr>
</tbody>
</table>
دریافت فوری متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات