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Spectrally selective absorber coating of WAlN/WAlON/Al_2O_3 for solar thermal applications

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ABSTRACT

A novel WAlN/WAlON/Al_2O_3 coating was successfully deposited on stainless steel (SS) substrate using reactive DC and RF magnetron sputtering. Excellent spectrally selective property with a high absorptance of 0.958 in the solar spectrum region and low emittance of 0.08 in the infrared region were achieved by tailoring the target power, deposition time and the reactive flow rates of N_2 and O_2. In the present solar selective coating, W layer acts as a back reflector and diffusion barrier, WAlN as the main absorber layer, WAlON as the semi-absorber layer, whereas the topmost Al_2O_3 layer works as an anti-reflecting layer. In reference to the thermal stability, the absorber deposited on SS substrates exhibited high solar selectivity (α/ε) of 0.920/0.11, when heat treated in air up to 500 °C for 2 hrs. Taken together, the present study demonstrated that the WAlN/WAlON/Al_2O_3-based selective absorbing coating with excellent thermal stability could be a promising material for photo-thermal conversion at temperatures of up to 500 °C.

1. Introduction

Concentrating solar power (CSP) system is one of the technologically emerging approaches, which can be implemented to convert the enormous amount of solar energy to usable form of energy, like electricity or heat [1,2]. The efficiency of these systems strongly depends on the solar selective absorber coating deposited on the metallic receiver tube. An ideal solar selective absorber coating should exhibit a high absorptance ($\alpha \geq 0.95$) in the wavelength range of 0.3–2.5 μm and a low emittance (≤ 0.10) in the infrared region ($2.5 \leq \lambda \leq 25$ μm) [3,4]. In addition, a solar selective absorber coating should have excellent thermal stability at high temperature (≥ 400 °C) [5]. A number of techniques such as, electrodeposition, physical vapor deposition, chemical vapor deposition, sol-gel, paint technology, etc. have been used to fabricate the solar selective coatings [6–10]. To address the high temperature stability of the coatings, environment friendly magnetron sputtering technology with various advantages, like large area deposition, high deposition rates, reproducibility, precise control in thickness and deposition parameters, etc. has become popular to develop these coatings in last several decades [10].

To achieve superior spectral selectivity and high temperature stability, a variety of solar selective coatings, such as single-layer cermet coatings, absorber-reflector tandem, semiconductor coatings, metal-dielectric composite coatings etc. have been studied and reported elsewhere [11,12]. One important reason limiting the use of the single layer cermet coatings is that their optical property degrades quickly at high temperature due to change in their microstructure and oxidation. In order to ensure the persistency of the coating at elevated temperature, one of the promising structures is the tandem absorber with graded metal concentration profile. Such designed structure consists of an anti-reflection surface layer of a transparent ceramic material, two solar absorptive intermediate layers and an IR-reflective metallic layer deposited on a metallic substrate [13].

Recently, transition metal nitrides and oxynitrides-based coatings have become popular as solar selective absorber due to their chemical inertness, outstanding spectral selectivity, superior chemical, mechanical, thermal stability and excellent oxidation

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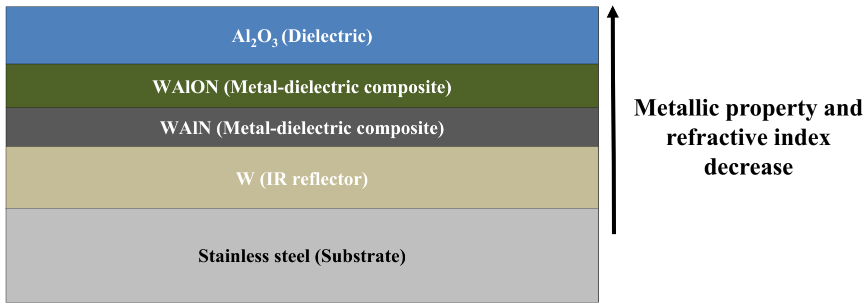

Fig. 1. Schematic diagram of the W/WAlN/WAlON/Al_2O_3 tandem absorber. Graded metallic profile has been designed [61–63].

resistance [14–16]. In particular, the tandem absorber coatings have been extensively investigated by a number of groups. For example, Ouyang et al. reported that TiAlN/TiAlSiN/Si_3N_4 coatings, deposited on SS substrates can exhibit high absorptance of 0.938 and thermal emittance of 0.09 [17]. According to Wang et al., NbTiON/SiON absorber coating, prepared on Cu substrate showed high selectivity with an absorptance value of 0.95 and emittance value of 0.07 [18]. Barshilia et al. studied TiAlN/TiAlON/Si_3N_4 and NbAlN/NbAlON/Si_3N_4 and these tandem absorbers showed high absorptance of 0.958 and 0.956, respectively and low emittance of 0.07 for both the coatings [19,20]. In a different work, Wang et al. reported that high absorptance of 0.948 and low emittance of 0.05 could be achieved by multilayered coating of Al/NbMoN/NbMoON/SiO_2 on SS substrates [21]. In another study, Zou et al. reported a CrAlN–CrAlON based tandem absorber that exhibited a high absorptance of 0.984 and a low emittance of 0.07 [22]. These studies suggest that if a coating is fabricated, while replacing the transition metal with tungsten, the desired spectral selectivity can be obtained.

In the present W/WAlN/WAlON/Al_2O_3 coating, WAlN acts as the main absorber layer, WAlON acts as the semi absorber layer and Al_2O_3 works as the anti-reflection layer. The metallic content of the absorber layers decreased from substrate to surface and such gradation enables to change the property of the layers from metallic to dielectric. The structure of the absorber coating has been presented in Fig. 1.

The structural, chemical, and optical properties of WAlN/WAlON/Al_2O_3-based tandem absorber coatings have been investigated using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), micro-Raman spectroscopy, solar spectrum reflectometer and emissometer, UV-Vis-NIR spectrophotometer and Fourier transform infrared spectroscopy (FTIR). The optical properties of the coatings have been investigated in air in the range of 350–550 °C.

2. Experimental

2.1. Coating deposition

W/WAlN/WAlON/Al_2O_3 spectrally selective coatings were developed on stainless steel (35 mm × 35 mm × 2 mm) by reactive DC/RF magnetron sputtering using high purity (> 99.9%) W, Al and Al_2O_3 target, respectively at constant target current, substrate bias and substrate temperature. A pulsed DC power supply was used to deposit W, WAlN and WAlON layers and a RF generator was used to deposit the Al_2O_3 layer. Before being put in the vacuum chamber, the substrates were polished and were degreased by sonication in acetone and isopropyl alcohol. The dried substrates were mounted on a rotatable substrate holder inside the vacuum chamber. W, Al and Al_2O_3 targets have a diameter of 150 mm and thickness of 8 mm. A base pressure of 8.5×10^{-6} mbar was created inside the sputtering chamber, which was equipped with a turbomolecular pump. Prior to the deposition, the targets were cleaned by sputtering for 10 min with a bias voltage of −800 V in pure Ar atmosphere. The distance between substrate and sputtering target was 10 cm. The sputtering gas, Ar with a purity of 99.99% and the reactive gases, O_2 and N_2, with a purity of 99.99% were injected to the sputtering chamber separately and adjusted by standard mass flow controllers. The chamber pressure was controlled by a manual valve mounted between the chamber and pump to get the desired pressure. The W interlayer was deposited in Ar-plasma by the non-reactive sputtering of W target with a power density of 3.114 W/cm^2. The WAlN, WAlON and Al_2O_3 layers were prepared from the reactive sputtering of W, Al and Al_2O_3 targets in Ar+N_2, Ar+N_2+O_2 and Ar+O_2 plasma, respectively. The Ar gas flow was kept constant at 28 sccm, while depositing W, WAlN and WAlON layers. The nitrogen flow rate was 26 and 21 sccm for WAlN and WAlON layers, respectively while the O_2 gas flow rate for WAlON layer was 9 sccm. For the deposition of WAlN layer, the power densities of W and Al targets were 1.698 and 2.265, respectively. Sputtering of WAlON layer was carried out at a power density of 1.982 and 2.548 W/cm^2 for W and Al, respectively. The top Al_2O_3 layer was deposited at a power density 6.582 W/cm^2 of Al_2O_3 target in Ar and O_2 gas flow rate of 20 and 2 sccm, respectively. The time of deposition for W, WAlN, WAlON and Al_2O_3 layers are 15, 6, 6 and 6.5 min, respectively. The sputtering parameters for an optimized coating are summarized in the Table 1. Also, the effect of the deposition time on the selective property of the coating has been presented in Table 2.

2.2. Coating characterization

The phase assemblage of the film was investigated by X-Ray Diffractometer (Bruker, D8) with Cu-K_α (40 kV, 40 mA, λ=0.15406 nm) radiation in the 2θ range of 10–60°. The chemical composition and bonding structure of the coatings, deposited on Si substrates were probed by X-ray photoelectron spectroscopy (SPECS), using non-monochromatic Al K_α radiation (1486.8 eV). The binding energies reported here were calculated with reference to C 1s peak at 284.5 eV with a precision of 0.1 eV. Surface topography of the sample was studied using atomic force microscopy (AFM, Bruker) with a silicon nitride tip of radius 50 nm in contact mode. A DILOR-JOBIN-YVON-SPEX integrated micro-Raman spectrometer (Model Labram) was used to obtain the Raman spectra.

The total hemispherical absorptance and emittance of the tandem absorber were measured using solar spectrum reflectometer and emissometer (M/s. Devices and Services). The reflectometer and emissometer were calibrated with standard samples. The absorptance was measured at room temperature, whereas, for the emittance measurements, the emissometer detector was heated to 82 °C. The accuracies of the measured absorptance values are ±2% and the emissometer has a repeatability