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Effects of substrates, film thickness and temperature on thermal emittance of Mo/substrate deposited by magnetron sputtering

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ABSTRACT

The thermal emittance of the Mo film, as an IR-reflector in solar selective absorbing coatings, is the most important property. The effects of the substrate material, the substrate surface roughness, the film thickness and the temperature on the thermal emittance of the Mo/substrate have been investigated. A series of Mo films with increasing film thickness were deposited on two types of substrate materials (glass and stainless steel). A saturated Mo thickness of 50 nm is found to produce the lowest thermal emittance. The thermal emittance of the Mo film is reduced by decreasing the substrate surface roughness. The emittance of the optimal Mo film remains 0.05 from 25 °C to 400 °C, which can meet the optical requirements for the IR-reflector.

1. Introduction

Solar selective absorbing coating (SSAC) is designed to maximize photothermal conversion efficiency. Namely, it should maximally absorb solar radiation corresponding to blackbody radiation at 5777 K from 0.3 μm to 2.5 μm and minimally emit the infrared (IR) thermal radiation from 2.5 μm to 20 μm at working temperature (100 °C–400 °C) [1,2]. The thermal energy transferred from the absorbed solar energy is taken away by the heat transfer fluid for electric power application as shown in Fig. 1. Hence an ideal SSAC should both have a high solar absorptance α (close to one) in solar radiation range and a low thermal emittance ε (close to zero) in IR range. The typical double cermet coating structure from surface to substrate (steel tube in Fig. 1) consists of a ceramic anti-reflection layer, a low and a high metal volume fraction cermet solar absorption layers (LMVF and HMVF), and a metal IR-reflector layer [3] as shown in Fig. 2.

The performance for SSAC is characterized by the photothermal conversion efficiency [4] given in Eq. (1), which should be close to the maximum value one.

$$\eta_T = \alpha - \frac{\sigma T^4}{CI}\varepsilon_T \qquad (1)$$

where α is solar absorptance, ε_T is the thermal emittance at temperature T of the SSAC, σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \mathrm{W/m^2\,K^4}$), I is the irradiance (typically 1000 W/m^2) and C is solar concentration (for parabolic trough typically $C = 80$). Thus enhancing solar absorptance and suppressing thermal emittance are effective methods to improve the photothermal conversion efficiency according to Eq. (1). The solar absorptance for most SSACs [5–7] have approached to maximum value one, whereas it is difficult to decrease the thermal emittance of SSACs to zero. To improve the photothermal conversion efficiency, it is effective to reduce the thermal emittance of SSACs.

Reduction of thermal emittance of the metal IR-reflector layer is a crucial method to inhibit the thermal emittance of the SSAC [8]. The preparation parameters of the metal layer have an important effect on the emittance. The emittance is decreased with decrease

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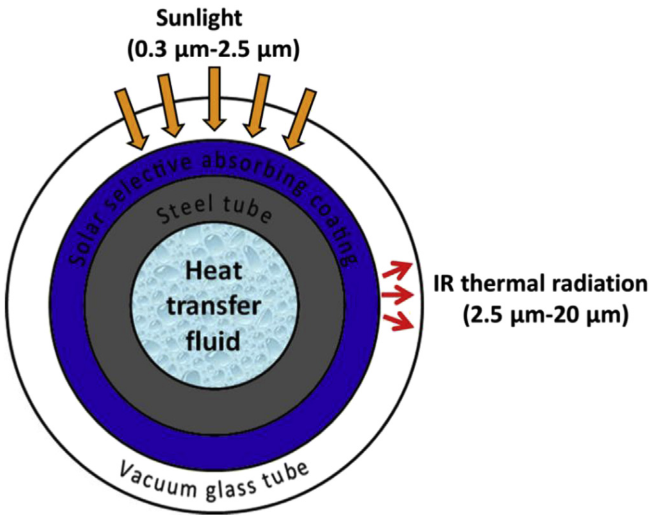

Fig. 1. Cross section of the receiver tube used in the parabolic trough collector (a kind of solar thermal collector).

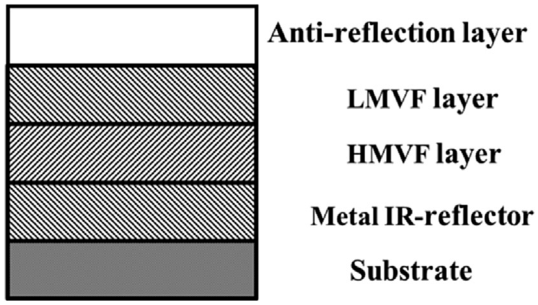

Fig. 2. Schematic diagram of the typical double cermet layer structure for SSAC.

in the sputtering gas pressure [9–13] and increase in the target power [14,15], due to the great change in the microstructure of the metal layer [9]. Thus, the low working gas pressure and high target power were used to prepare the metal IR-reflector in this paper. The recent results have shown that the emittance of the Au film and W film is reduced by decreasing the substrate surface roughness [16,17], which is also verified by the result in this paper.

The metal IR-reflector layer should have not only high reflectance in the IR range but also excellent thermal stability at elevated temperature. Molybdenum (Mo) possesses high melting point (2623 °C) among all the metals. In addition, the SSACs of NiAl-Al_2O_3 and Mo-SiO_2 used Mo films as IR-reflector have high thermal stability at 500 °C [18], 600 °C [19] and 800 °C [20] in vacuum respectively. Hence, high IR reflecting Mo is a promising candidate as an IR-reflector layer [7,21–23]. In addition, Mo is also used as a back contact and its optical properties are quite important in thin film solar cell community [12,13]. In this paper, the magnetron sputtering is used to deposit the Mo film [20,24,25] and stainless steel (SS) is selected as the substrate for the industrial production requirement. The effects of the substrate materials, substrate surface roughness, film thickness and temperature on the emittance of the Mo/substrate have been studied in detail. The SSAC of SiO_2/ZrSiON/ZrSiN/Mo is prepared, in which the optimized Mo film is used as the IR-reflector.

2. Experiments

Stainless steels 304 (304SS) and glass are used as substrates. The 3D parameter average roughness (Sa) is defined as the arithmetic mean of the absolute value of the deviation from the mean height [26], given by Eq. (2).

$$\mathrm{Sa} = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left|z\left(x_i, y_j\right) - \mu\right| \tag{2}$$

Where $\mu = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} z(x_i, y_j)$ is the mean height. An equally spaced digitised 3D surface, can be denoted by z (x_i, y_j) (x_i = iΔx, y_j = jΔy; i = 1, 2, … M; j = 1, 2, … N), where Δx and Δy are the sampling intervals, and M and N represent the number of sampling points in the x and y directions, respectively. The values of Sa of all the substrates are listed in Table 1. The SS1, SS2 and SS3 denote the stainless steels with the polished surface, the specific treated surface and the sand blasting surface respectively. The surface treatment for the SS2 substrate includes four steps: cold rolling, heat treatment, acid pickling or dephosphorization, bright annealing. The Mo films with thickness range of 6–180 nm, 10–250 nm and 10–10000 nm were deposited on glass, SS1-2 and SS3 substrates by a JGP350C magnetron sputtering equipment as shown in Fig. 3 [24]. The size of Mo target is Φ60 mm × 4 mm with a purity of 99.95%. All substrates were cleaned with alcohol followed by de-ionized water in an ultrasonic agitator and blow-dried before being deposited. The detailed preparation parameters are listed in Table 2.

The thermal emittance for the opaque sample and semi-transparent sample is calculated according to Eq. (3) and Eq. (4), respectively [27]. Intensity distribution of the blackbody radiation at temperature from 25 °C to 400 °C is in the wavelength range of 1–100 μm, and the main intensity distributes in the wavelength range of 1–20 μm.

$$\varepsilon_{(25^\circ C-400^\circ C)} = \frac{\int_{1\mu m}^{100\mu m}(1 - R(\lambda))I_b(\lambda, T)\mathrm{d}\lambda}{\int_{1\mu m}^{100\mu m} I_b(\lambda, T)\mathrm{d}\lambda} \tag{3}$$

$$\varepsilon_{(25^\circ C-400^\circ C)} = \frac{\int_{1\mu m}^{100\mu m}(1 - R(\lambda) - \tau(\lambda))I_b(\lambda, T)\mathrm{d}\lambda}{\int_{1\mu m}^{100\mu m} I_b(\lambda, T)\mathrm{d}\lambda} \tag{4}$$

Where $I_b(\lambda, T)$ is the blackbody radiation at the given temperature T. Reflectance $R(\lambda)$ and transmittance $\tau(\lambda)$ are measured at normal incidence and room temperature. All samples are opaque except for the samples of 6–50 nm thick Mo films on glass substrate.

The solar absorptance (α) is weighted by the solar spectral radiation $I_s(\lambda)$ as shown in Eq. (5). The main solar energy (more than 95%) distributes from 0.3 μm to 2.5 μm.

Table 1
The surface average roughness (Sa) of all the substrates and the emittance (100 °C) of 50 nm Mo/substrate.

Substrates	SS1	Glass	SS2	SS3
Sa (nm) of substrate	1	3	23	1497
Emittance (100 °C) of 50 nm Mo/substrate	0.05	0.07	0.08	0.32