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# Investigation on low thermal emittance of Al films deposited by magnetron sputtering

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## HIGHLIGHTS

- Optimal thickness 78 nm of Al film for lowest emittance is obtained.
- Emittance of optimal Al film keeps close to 0.02 from 25 °C to 400 °C.
- Optical constants of Al film are deduced by fitting R and T spectra.

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## ABSTRACT

A series of Al films with different thicknesses were deposited on polished stainless steel by direct current (DC) magnetron sputtering as a metal IR-reflector layer in solar selective absorbing coating (SSAC). The effects of the film thickness and the temperature on the thermal emittance of the Al films are studied. An optimal thickness 78 nm of the Al film for the lowest total thermal emittance is obtained. The thermal emittance of the optimal Al film keeps close to 0.02 from 25 °C to 400 °C, which are low enough to satisfy the optical requirements in SSAC. The optical constants of the Al film are deduced by fitting the reflectance and transmission spectra using SCOUT software.



## 1. Introduction

Solar selective absorbing coatings (SSACs) which are one of the key elements of the solar collectors are used as the photothermal conversion surface [1–4]. An ideal SSAC should both have a high absorptance (near one) in the solar spectrum range (0.3–2.5 μm), and a low thermal emittance (near zero) in the thermal infrared range (>2.5 μm) as shown in Fig. 1 [5,6]. The typical double cermet layer structure of SSAC from surface to substrate is showed in Fig. 2, which is composed of the following: (i) an antireflection (AR) layer that enhances solar transmission; (ii) a low metal volume fraction (LMVF) cermet solar absorption layer, a high metal volume fraction (HMVF) cermet solar absorption layer, which forms interference absorption bilayer; (iii) a metal IR-reflector layer that reduces the thermal emittance from the substrate; (iv) a substrate [7,8].

The optical properties of the SSAC are characterized by two important parameters: solar absorptance ($\alpha$) and thermal emittance ($\varepsilon$). Generally, $\alpha \geqslant 0.95$ and $\varepsilon \leqslant 0.05$ at room temperature are necessary for the requirement of optical property of a SSAC. The stainless steel (SS) is always used as the substrate in the industry production for its low costs and high temperature stability. But the thermal emittance of the SS is high, such as $\varepsilon$(25 °C) = 0.10 for a 304SS with a polished surface. A metal IR-reflector layer with a low emittance must be deposited on the SS substrate in order to reduce the thermal emittance of the SS substrate. When the upper three layers (HMVF, LMVF and AR) are deposited sequentially on the metal IR-reflector, the chemical structure of the metal IR-reflector keeps stability and the interface forms between the metal IR-reflector and the upper HMVF layer [9–12]. Thus the thermal emittance of the metal IR-reflector maintains. And the thermal emittance increment after depositing the upper three layers can

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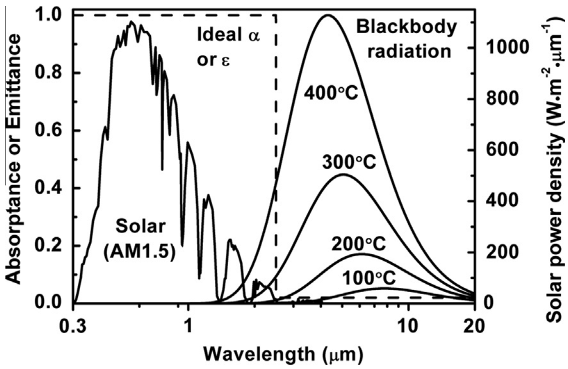


**Fig. 1.** The absorptance or emittance spectrum of an ideal solar selective absorbing coating (SSAC).

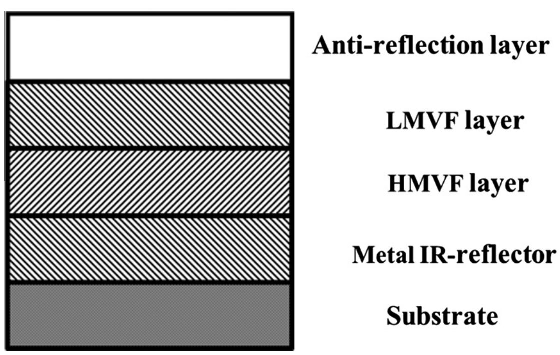


**Fig. 2.** Schematic diagram of the typical double cermet layer structure for solar selective absorbing coating (SSAC).

be minimized by tuning the extinction coefficient to zero in the thermal infrared range or reducing the film thicknesses of the upper three layers [13,14]. The metal IR-reflector layer with low emittance is essential to obtain a low emittance for SSAC [11,15]. Therefore, it is important to choose appropriately and prepare successfully a metal layer with low emittance for SSAC.

According to Hagen–Rubens relation [16] for the long wavelength radiation, the normal reflectance of the metal is obtained from Eq. (1):

$$\rho_n^s = 1 - 0.365\sqrt{\gamma/\lambda} \quad (1)$$

$\lambda$ is wavelength (cm) and $\gamma$ is electrical resistivity (Ω·cm). Therefore the smaller the electrical resistivity is, the higher the normal reflectance of the metal, which is the theoretical foundation to choose metal with high IR reflectance. The reasons for selecting the metal Al as the metal IR-reflector are as follows. The metal Al with very low electrical resistivity will ensure high IR reflectance, i.e. low thermal emittance. SSACs with Al metal IR-reflector have low thermal emittance, such as Al/M-AlN/AlN: $\varepsilon$(25 °C) = 0.03–0.04, $\varepsilon$(350 °C) = 0.07–0.10 [17]; Al/W-AlON/AlON: $\varepsilon$(80 °C) = 0.051 [13]; Al/Zr–$ZrO_2$/$Al_2O_3$: $\varepsilon$(80 °C) = 0.049 [18]; Al/$Ti_xAl_yN$/AlN: $\varepsilon$(82 °C) = 0.04–0.06 [10]; Al/NbMoN/NbMoON/$SiO_2$: $\varepsilon$(80 °C) = 0.05 [19]. Additionally, the metal Al is cheaper and the SSACs using the metal Al as the IR-reflector have good thermal stability up to 400 °C both in vacuum and air [10,19]. But the detailed information about the relationship between the emittance of the Al films and the film thickness, temperature, etc. has not been reported so far. Considering the widely usage of the Al films in SSACs, it is valuable to study the thermal emittance and relevant optical properties of the Al films.

According to our research, the substrate surface condition has a great influence on the thermal emittance of the metal films on it and the smooth substrate surface can ensure a low emittance of the metal films. Thus, the 304SS with mirror polished surface, of roughness average (*Sa*) 1.01 nm is used as the substrate to eliminate the effect of substrate surface conditions.

In this paper, the Al films were prepared on 304SS substrate with mirror polished surface by DC magnetron sputtering as the IR-reflector metal layer in SSAC. The effect of the film thickness on the thermal emittance is studied and the optimal thickness which makes the thermal emittance the lowest is obtained. The effect and reason of the temperature on the thermal emittance are discussed. Moreover, the structure, morphologies and optical constants of the Al films are investigated in detail.

## 2. Experiments

The Al films were deposited by a JGP350C magnetron sputtering equipment. The size of Al target is Φ60 mm × 3 mm. The substrates were chemically cleaned in an ultrasonic agitator using alcohol followed by de-ionized water rising and air drying before being deposited. The detailed preparation parameters are in Table 1.

The crystal structure of the Al film was characterized by X-ray diffraction (XRD) on a Dmax diffractometer with Cu Kα radiation. The surface morphologies of the Al film and substrate surface roughness were observed by scanning electron microscopy (SEM) FEI XLS30 and atomic force microscopy (AFM) CSPM400. The film thickness was measured using a Dektak 6 M surface profiler.

Normal reflectance data were measured by spectrometer L900 (0.3–2.5 μm) and Fourier Transform Infrared Reflectance (FTIR) spectrometer Bruker Tensor 27 (2.5–22 μm). The reflectance data in the range of 23–100 μm are extrapolated. Both instruments are equipped with integrated spheres to reduce scattering effect. The total thermal emittance with a normal angle of radiation is calculated according to Eq. (2) which is weighted by the blackbody radiation, for the given temperature $T$ [20], where $\lambda_1$ depends on temperature and $\lambda_2$ = 100 μm.

$$\varepsilon_T = \frac{\int_{\lambda_1}^{\lambda_2}(1 - R(\lambda))I_b(\lambda, T)d\lambda}{\int_{\lambda_1}^{\lambda_2} I_b(\lambda, T)d\lambda} \quad (2)$$

## 3. Results and discussion

### 3.1. Structure and morphologies of the Al film

The measured XRD pattern of the Al film is showed in Fig. 3. The Al film with cubic structure (PDF: 04-0787) grows preferentially along the (1 1 1) direction. The smooth and dense surface of the Al film with the thickness of 78 nm on SS substrate is showed in Fig. 4. The surface average roughness (*Sa*) of the SS substrate is 1.01 nm and increased to 4.08 nm when the Al film with the thickness of 78 nm was deposited on the SS substrate (see Fig. 5).

**Table 1**
Parameters for the deposition of the Al films.

| Sputtering method | DC |
|---|---|
| Base vacuum | $1 \times 10^{-3}$ (Pa) |
| Substrate-to-target distance | 60 (mm) |
| Ar gas flow rate | 50 (sccm) |
| Sputtering pressure | 0.3 (Pa) |
| Target power density | 7.2 (W/cm$^2$) |