Metal–AlN cermet solar selective coatings deposited by direct current magnetron sputtering technology

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Abstract. A series of metal–aluminium nitride (M–AlN) cermet materials for solar selective coatings was deposited by a novel direct current (d.c.) magnetron sputtering technology. Aluminium nitride was used as the ceramic component in the cermets, and stainless steel (SS), nickel-based alloy $Ni_{80}Cr_{20}$ (NiCr), molybdenum-based alloy $Mo_{99}Ti_{0.5}Zr_{0.1}$ (TZM) and tungsten were used as the metallic components. The aluminium nitride ceramic and metallic components of the cermets were deposited by simultaneously running both an aluminium target and another metallic target in a gas mixture of argon and nitrogen. The ceramic component was deposited by d.c. reactive sputtering and the metallic component by d.c. non-reactive sputtering. The total sputtering gas pressure was 0.8–1.0 Pa and the partial pressure of reactive nitrogen gas was set at 0.020–0.025 Pa which is sufficiently high to ensure that a nearly pure AlN ceramic sublayer was deposited by d.c. reactive sputtering. Because of the excellent nitriding resistance of stainless steel and the other alloys and metal, a nearly pure metallic sublayer was deposited by d.c. sputtering at this low nitrogen partial pressure. A multilayered system, consisting of alternating metallic and AlN ceramic sublayers, was deposited by substrate rotation. This multisublayer system can be considered as a macrohomogeneous cermet layer with metal volume fraction determined by controlling the thicknesses of metallic and ceramic sublayers. Following this procedure, M–AlN cermet solar selective coatings with a double cermet layer structure were deposited. The films of these selective surfaces have the following structure: a low metal volume fraction cermet layer is placed on a high metal volume fraction cermet layer which in turn is placed on an aluminium metal infrared reflection layer. The top surface layer consists of an aluminium nitride antireflection layer. A solar absorptance of 0.92–0.96 and a normal emittance of 0.03–0.05 at room temperature have been achieved for these M–AlN cermet solar selective coatings.

1. Introduction

A large number of solar selective surfaces have been studied [1–3]. Most solar selective coatings use metal–dielectric composites, known as cermets, as the absorber of solar energy. They vary mainly in their optical properties and thermal stability. Electroplated black chromium, which employs $Cr–Cr_2O_3$ cermet material, is the most widely used solar absorber [4, 5]. Nickel-pigmented anodic Al_2O_3 solar absorber, which is produced by electrochemical treatment of an aluminium sheet, is another popular solar selective absorber [6, 7]. The costs of the production of these two kinds of solar coatings are low, so they are widely used in flat plate solar collectors. However, the emittance of both coatings is high, around 15–20% at 100 °C.

Magnetron sputtering technology is also suitable for large-area deposition of thin films with a relatively high deposition rate and has been used for the deposition of solar selective coatings with less environmental pollution

than electrochemical methods. Furthermore, improved optical properties of solar selective coatings have been achieved by using sputtering technology. Selective surfaces incorporating d.c. reactively sputtered stainless steel–carbon (SS–C) were intensively studied in the 1970s and 1980s [8–12]. The all-glass evacuated solar collector tubes using sputtered SS–C cermet have been mass-produced. Two cylindrical targets, stainless steel and copper, were employed to deposit SS–C cermet solar coatings onto batches of tubes. Two targets were run independently. The Cu target was used for deposition of a Cu metal infrared reflection layer using d.c. sputtering in pure argon gas. The SS–C cermet solar absorber layer was deposited by d.c. reactive sputtering, running the SS target in a gas mixture of argon and acetylene (C_2H_2). A solar absorptance of 0.92–0.93 and emittance of 0.03–0.04 at 100 °C were achieved. Reactive sputtered Al–N cermet solar coating is another successful solar coating [13–16]. The all-glass evacuated solar collector tubes incorporating d.c.

reactively sputtered Al–N cermet have been mass-produced in China. Only an Al cylindrical target is employed to deposit Al–N cermet solar coatings onto batches of tubes. An Al metal layer is deposited as the infrared reflection layer using d.c. sputtering in pure argon gas. The Al–N cermet solar absorber layer is deposited by d.c. reactive sputtering in a gas mixture of argon and nitrogen. A solar absorptance of 0.92–0.93 and emittance of 0.06 at 100 °C were achieved [16]. In this commercial-scale coater the Al target materials are efficiently used. However, these Al–N cermet solar coatings are only stable at lower operating temperatures (up to 200 °C) than those of SS–C cermet selective surfaces. These SS–C and Al–N cermet solar collector tubes have been widely used in solar hot water applications.

The solar collector tubes for solar thermal electricity plants of a LUZ Solar Electric Generating System (SEGS) type use Mo–Al_2O_3 cermet materials as the solar absorber, because of the excellent thermal stability of materials at high operating temperatures. Planar magnetron technology was used to deposit this cermet solar selective surface onto solar collector tubes. Seven planar targets, including three Mo metallic targets and four Al_2O_3 ceramic targets, were used to produce the Mo–Al_2O_3 cermet solar collector tubes in a commercial-scale coater [17]. The Mo–Al_2O_3 cermet solar coatings were deposited onto a tube located at the centre of a chamber by translating the tubular substrate past the different cathodes, while rotating it axially. The Mo metal component in the cermet was deposited using d.c. sputtering, and the Al_2O_3 ceramic component in the cermet was deposited by radio-frequency (rf) sputtering. A solar absorptance of 0.96, and emittance of 0.10 at 100 °C and 0.16 at 350 °C have been achieved using this coater. For the planar rf sputtered ceramic component in the cermet, the deposition rate is lower, and the cost of deposition equipment is much higher compared with reactively sputtered SS–C and Al–N cermet solar coatings [18]. The Mo–Al_2O_3 cermet solar coatings are therefore more expensive than d.c. reactively sputtered SS–C and Al–N cermet solar coatings which are also produced using a cylindrical d.c. sputtering coater.

Recently, we have studied a series of new cermet materials for solar coatings deposited by a novel d.c. magnetron sputtering technology. This invention has two main innovative features: (i) the ceramic and metallic components in the cermet are simultaneously deposited by d.c. sputtering; (ii) the ceramic component is deposited by d.c. reactive sputtering and the metallic component by d.c. non-reactive sputtering. A patent application related to this invention has been lodged [19]. In this article a study of solar selective coatings incorporating a series of metal–aluminium nitride cermet materials as solar absorber is described. AlN is used as the ceramic component in the cermet. Stainless steel, $Ni_{80}Cr_{20}$, molybdenum-based alloy TZM and tungsten are used as the metallic components. A solar absorptance of 0.92–0.96 and emittance of 0.03–0.05 at room temperature has been achieved for several deposited M–AlN cermet solar selective coatings.
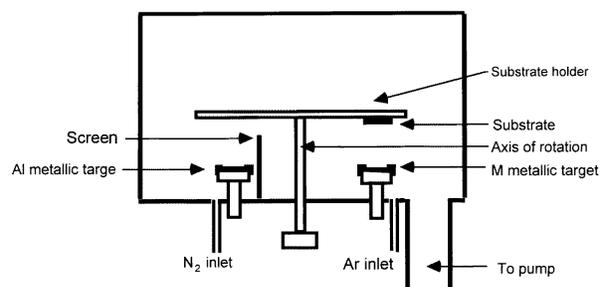

Figure 1. Schematic diagram of the planar d.c. sputtering apparatus for the deposition of M–AlN cermet solar selective coatings. Both Al and M metallic targets are mechanically clamped to copper electrodes at nearly the same horizontal level. An SS, $Ni_{80}Cr_{20}$, TZM and W target is used as the M metallic target. The substrate is clamped to the substrate holder which can be rotated.

2. Experimental details

The M–AlN cermet selective surfaces were deposited using a planar d.c. magnetron sputter coater, shown schematically in figure 1. Two planar sputtering sources are mounted horizontally on the base of a vacuum chamber. Al (99% purity) and M metallic targets are mechanically clamped to water cooled copper electrodes at nearly the same horizontal level. An SS (type AISI 316), NiCr ($Ni_{80}Cr_{20}$), TZM (99% Mo, 0.5% Ti, 0.1% Zr) and W (99.9% purity) target is used as the M metallic target. Both Al and M targets have a diameter of 50 mm. The aluminium target is 2 mm thick. The thickness of the SS and NiCr targets is 3 mm, and the thickness of the TZM and W targets is 1 mm. A substrate holder is placed about 75 mm above the targets, and can be rotated around a vertical axis. The Al and M targets are equidistant from the substrate holder rotation axis. The reactive nitrogen gas was injected into the chamber close to the Al target, and argon sputtering gas was injected near the M target. Both the Ar and N_2 gas injection flow rates into the vacuum chamber may be adjusted independently using two separate mass flow controllers.

During the deposition of the M–AlN cermet layer, both Al and M targets were run simultaneously in a gas mixture of argon and nitrogen. The total sputtering gas pressure $P(Ar + N_2)$ was 0.8–1.0 Pa, and the reactive nitrogen gas partial pressure $P(N_2)$ was chosen to be 0.020–0.025 Pa, well beyond the transition point from Al metallic phase to AlN ceramic phase in the deposited material. For the deposition of an M–AlN cermet layer the substrate was rotated to be above the Al target (or M target) and was held there for a few seconds. A nearly pure AlN sublayer was deposited by d.c. reactive sputtering. Then the substrate was rotated to above the M target and held there for a few seconds. Because of the excellent nitriding resistance of M metal, a nearly pure M sublayer was deposited by d.c. sputtering at this low nitrogen partial pressure. Next, the substrate was rotated back to above the Al target for the deposition of another AlN sublayer. By repeating this procedure, a multisublayer system, consisting of alternating AlN ceramic and M metallic sublayers, was deposited. These substrate movements are controlled electrically. The
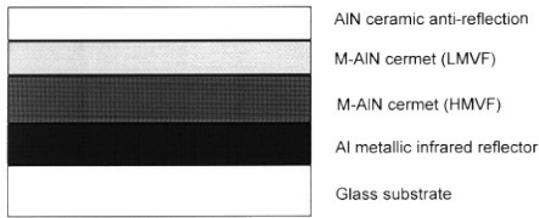
Figure 2. Schematic diagram of a double cermet layer structure of deposited M–AlN solar selective coatings.
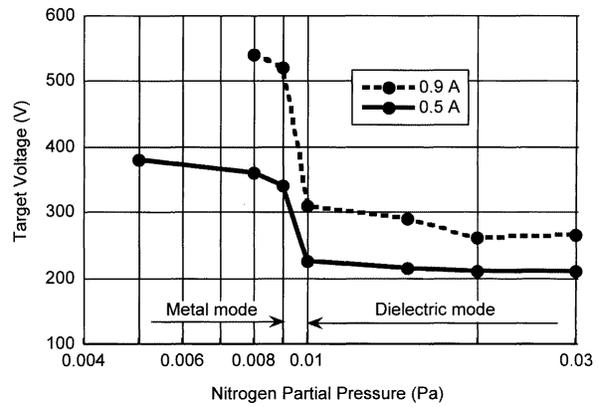

Figure 3. The dependence of cathode voltage on the nitrogen partial pressure for two Al target currents, 0.5 A (full curve) and 0.9 A (broken curve) at a total argon and nitrogen pressure of 1 Pa in steady-state operation of an Al planar magnetron sputtering source.

deposition time for the M and AlN sublayers may be controlled independently. By control of sputter currents and deposition times the thickness of each of the AlN ceramic and M metallic sublayers was deposited to be less than 3 nm. This multisublayer system typically consists of 10–50 sublayers. As a result it can be considered as a macrohomogeneous M–AlN cermet layer [20].

In this study M–AlN cermet selective surfaces with a double cermet layer structure were deposited. Figure 2 shows the typical film structure of M–AlN cermet selective surfaces deposited from surface to substrate: it consists of

(i) an anti reflection layer composed of a transparent AlN ceramic material that enhances solar absorption;

(ii) an absorbing layer composed of two homogeneous M–AlN cermet layers, a low metal volume fraction (LMVF) cermet layer on a high metal volume fraction (HMVF) cermet layer;

(iii) an Al metal infrared reflector layer which reduces substrate emittance; and

(iv) a glass substrate.

For the deposition of M–AlN cermet selective surfaces, the vacuum chamber was pumped by a rotary vane pump and a diffusion pump to a base pressure of $(5–8) \times 10^{-4}$ Pa. An Al infrared reflection layer was first deposited on a glass substrate in pure argon gas at a pressure of 0.1 Pa. Then a high metal volume fraction M–AlN cermet layer and a low metal volume fraction M–AlN cermet layer were deposited in succession using the method described above. The sputtering currents of both Al and M targets were maintained constant during the deposition of the two cermet layers. The different metal volume fractions in the two cermet layers were produced by changing the deposition time ratio of the M to the AlN sublayer. Finally, an AlN antireflection layer was deposited on the low metal volume fraction cermet layer by d.c. reactive sputtering at a nitrogen partial pressure of 0.06–0.08 Pa.

The deposition rates of the Al metal, the M–AlN cermet and the AlN ceramic for several different sputtering parameters were derived by measuring the thickness of deposited films using a Tencor P-10 surface profiler. The optical reflectance was measured with a Varian Cary 5E UV-VIS-NIR spectrophotometer in the wavelength range of 0.3–3.0 μm, and a Shimadzu IR-470 infrared spectrophotometer in the range of 2.5–25 μm.

3. Results and discussions

3.1. Reactive sputtering AlN

The AlN has a high decomposition temperature ($>2400\,°$C) which is an important property for the ceramic component in a cermet for high-temperature solar selective coatings. Reactively sputtered AlN thin films have been studied previously as dielectric materials for widespread applications [21–24]. Both d.c. and rf reactive sputtering technologies have been used for the deposition of these AlN films. The correct nitrogen partial pressure must be selected, in order to deposit aluminium nitride nearly free of the Al metal phase by d.c. reactive sputtering in this study. When aluminium is reactively sputtered in a gas mixture including reactive nitrogen gas, a transition from metallic to dielectric deposited layer occurs as the nitrogen partial pressure is increased [21]. Figure 3 shows the measured dependence of cathode voltage on the nitrogen partial pressure for two Al target currents of 0.5 A and 0.9 A while running this d.c. sputtering apparatus. The vacuum chamber was pumped to a base pressure of 8×10^{-4} Pa. The Al target was run at a total Ar and N_2 gas pressure of 1 Pa. The data of figure 3 clearly show that an abrupt transition from the metal to the dielectric occurs at around 0.009–0.01 Pa, and the position of the transition edge is nearly identical for currents of both 0.5 A and 0.9 A. It is noted that the vacuum gauge was not calibrated precisely, so the critical point record is a relative value. This transition N_2 partial pressure is very low. One can therefore use low relative N_2 gas flow to deposit AlN dielectric material by d.c. reactive sputtering.

3.2. SS–AlN cermet solar selective coatings

SS–AlN cermet selective surfaces with the double cermet layer film structure AlN/SS–AlN(LMVF)/SS–AlN(HMVF)/Al were deposited. Sputtering parameters for the deposition of SS–AlN solar selective films are listed in table 1.

Commonly quoted parameters of performance for selective surfaces are solar absorptance and thermal

Table 1. Sputtering parameters for the deposition of SS–AlN cermet solar selective films.

Layer	$P(Ar + N_2)$ (Pa)	$P(N_2)$ (Pa)	Current/voltage (A/V)	
			(Al target)	(SS target)
Al	0.1	—	0.40/380	—
SS–AlN (HMVF)	1	0.02	0.40/240	0.20/450
SS–AlN (LMVF)	1	0.02	0.40/240	0.20/450
AlN	1	0.06	0.40/220	—

emittance. The angular-dependent solar absorptance α and thermal emittance ε are defined, respectively, by

$$\alpha(\theta) = \left(\int_0^\infty A(\lambda)[1 - R(\theta, \lambda)]\,d\lambda \right) \left(\int_0^\infty A(\lambda)\,d\lambda \right)^{-1} \quad (1)$$

$$\varepsilon(\theta, T) = \left(\int_0^\infty E(T, \lambda)[1 - R(\theta, \lambda)]\,d\lambda \right)$$

$$\times \left(\int_0^\infty E(T, \lambda)\,d\lambda \right)^{-1} \quad (2)$$

where $A(\lambda)$ is the solar spectral radiance, and $E(T, \lambda)$ the spectral blackbody emissive power. $R(\theta, \lambda)$ is the angular-dependent spectral reflectance.

A solar absorptance of 0.93–0.96 and normal emittance of 0.03–0.04 at room temperature and 0.07–0.10 at 350 °C have been achieved for SS–AlN cermet selective surfaces. The solar performance parameters, solar absorptance α and normal emittance ε_n at 20 and 350 °C for several deposited SS–AlN cermet selective surface films are listed in table 2. Films F203SS1v and F209SS2v represent films F203SS1 and F209SS2 baked at 500 °C in a vacuum for 1 h. The absorptance was calculated using the measured near normal reflectance spectrum in the solar radiation region of 0.3–3.0 μm and the air mass 1.5 spectrum. The normal emittance was calculated in the thermal infrared region 1–50 μm, using the measured near normal reflectance values in the wavelength range of 1–25 μm and extrapolated values in the range of 25–50 μm, and the spectral blackbody emissive power. The emittance at 350 °C is an estimated value based on the reflectance spectrum at room temperature, but has been corrected by accounting for the temperature dependence of emissivity for an Al metal infrared reflector. The thicknesses of the layers in nm are also shown in table 2 in order of layers: AlN/SS–AlN(LMVF)/SS–AlN(HMVF)/Al.

As an example, a measured near normal reflectance spectrum in the wavelength range of 0.3–25 μm for the deposited SS–AlN cermet selective surface film F203SS3 is shown in figure 4. This reflectance spectrum corresponds to a solar absorptance of 0.96 and emittance of 0.04 at room temperature.

3.3. NiCr–AlN cermet solar selective coatings

NiCr–AlN cermet selective surfaces with the double cermet layer film structure AlN/NiCr–AlN(LMVF)/NiCr–AlN(HMVF)/Al were deposited. Sputtering parameters for the deposition of NiCr–AlN solar selective films are listed in table 3. A solar absorptance of 0.92–0.94 and
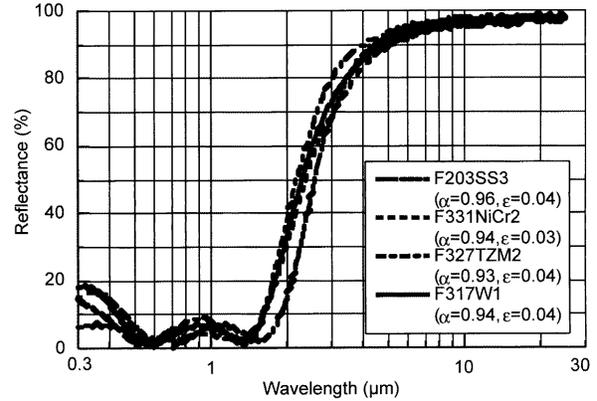

Figure 4. The measured near normal reflectance spectra for four deposited M–AlN cermet solar selective films, F203SS3, F331NiCr2, F327TZM2 and F317W1 with the double cermet film structure, AlN/M–AlN(LMVF)/M–AlN(HMVF)/Al.

emittance of 0.03–0.04 at room temperature and 0.08–0.10 at 350 °C have been achieved for NiCr–AlN selective surfaces. The solar performance and layer thicknesses of several deposited NiCr–AlN cermet solar selective films are listed in table 4.

A measured near normal reflectance spectrum in the wavelength range of 0.3–25 μm for a deposited NiCr–AlN cermet solar selective film F331NiCr2 is shown in figure 4. This reflectance spectrum corresponds to a solar absorptance of 0.94 and emittance of 0.03 at room temperature.

3.4. TZM–AlN cermet solar selective coatings

TZM–AlN cermet selective surfaces with the double cermet layer film structure AlN/TZM–AlN(LMVF)/TZM–AlN(HMVF)/Al were deposited. Sputtering parameters for the deposition of TZM–AlN solar selective films are listed in table 5. A solar absorptance of 0.92–0.93 and emittance of 0.03–0.04 at room temperature and 0.07–0.08 at 350 °C have been achieved for TZM–AlN cermet selective surfaces. The solar performance parameters and layer thicknesses of several deposited TZM–AlN cermet selective surface films are listed in table 6.

A measured near normal reflectance spectrum in the wavelength range of 0.3–25 μm for a deposited TZM–AlN cermet solar selective film F327TZM2 is shown in figure 4. This reflectance spectrum corresponds to a

Table 2. Solar performance and layer thicknesses of deposited SS–AlN cermet solar selective films.

Film	α	ε_n at 20 °C	ε_n at 350 °C	Thickness (nm) (AlN/SS–AlN(LMVF)/SS–AlN(HMVF)/Al)
F203SS1	0.94	0.03	0.08	72/16/64/200
F203SS1v[a]	0.94	0.03	0.08	
F203SS3	0.96	0.04	0.10	72/32/53/200
F209SS2	0.93	0.03	0.08	80/32/43/200
F209SS2v[a]	0.93	0.03	0.07	

[a] v for baked in a vacuum at 500 °C for 1 h.

Table 3. Sputtering parameters for the deposition of NiCr–AlN cermet solar selective films.

Layer	$P(Ar + N_2)$ (Pa)	$P(N_2)$ (Pa)	Current/voltage (A/V) (Al target)	Current/voltage (A/V) (NiCr target)
Al	0.1	—	0.40/540	—
NiCr–AlN (HMVF)	0.8	0.025	0.35/240	0.15/460
NiCr–AlN (LMVF)	0.8	0.025	0.35/240	0.15/460
AlN	0.8	0.08	0.35/250	—

Table 4. Solar performance and layer thicknesses of deposited NiCr–AlN cermet solar selective films.

Film	α	ε_n at 20 °C	ε_n at 350 °C	Thickness (nm) (AlN/NiCr–AlN(LMVF)/NiCr–AlN(HMVF)/Al)
F330NiCr1	0.92	0.04	0.08	81/66/38/200
F330NiCr2	0.93	0.04	0.09	76/48/51/200
F331NiCr1	0.94	0.04	0.10	72/30/70/200
F331NiCr2	0.94	0.03	0.09	70/36/64/200

Table 5. Sputtering parameters for the deposition of TZM–AlN cermet solar selective films.

Layer	$P(Ar + N_2)$ (Pa)	$P(N_2)$ (Pa)	Current/voltage (A/V) (Al target)	Current/voltage (A/V) (TZM target)
Al	0.1	—	0.40/540	—
TZM–AlN (HMVF)	0.8	0.025	0.35/240	0.15/330
TZM–AlN (LMVF)	0.8	0.025	0.35/240	0.15/330
AlN	0.8	0.08	0.35/250	—

solar absorptance of 0.93 and emittance of 0.04 at room temperature.

3.5. W–AlN cermet solar selective coatings

W–AlN cermet selective surfaces with the double cermet layer film structure AlN/W–AlN(LMVF)/W–AlN(HMVF)/Al were deposited. Sputtering parameters for the deposition of W–AlN solar selective films are listed in table 7. A solar absorptance of 0.92–0.94 and emittance of 0.03–0.05 at room temperature and 0.08–0.10 at 350 °C have been achieved for W–AlN cermet selective surfaces. The solar performance parameters and layer thicknesses of several deposited W–AlN cermet selective surface films are listed in table 8. Film F317W1v represents film F317W1 baked at 500 °C in a vacuum for 1 h.

A measured near normal reflectance spectrum in the wavelength range of 0.3–25 μm for the deposited W–AlN cermet solar selective film F317W1 is shown in figure 4. This reflectance spectrum corresponds to a solar absorptance of 0.94 and emittance of 0.04 at room temperature.

3.6. Discussions

A certain amount of M metal oxide and aluminium oxide will remain in the M–AlN cermet layers. This is due to the reaction of residual water vapour and oxygen gas in the vacuum chamber during sputtering. This is unlikely to affect solar performance in applications of interest. When sputtering M metal in a gas mixture of Ar and N_2, a small nitrogen content may exist in

Table 6. Solar performance and layer thicknesses of deposited TZM–AlN cermet solar selective films.

Film	α	ε_n at 20 °C	ε_n at 350 °C	Thickness (nm) (AlN/TZM–AlN(LMVF)/TZM–AlN(HMVF)/Al)
F324TZM1	0.92	0.03	0.07	70/47/46/200
F327TZM1	0.92	0.03	0.07	74/47/49/200
F327TZM2	0.93	0.04	0.08	78/47/52/200

Table 7. Sputtering parameters for the deposition of W–AlN cermet solar selective films.

Layer	$P(Ar + N_2)$ (Pa)	$P(N_2)$ (Pa)	Current/voltage (A/V) (Al target)	Current/voltage (A/V) (W target)
Al	0.1	—	0.50/380	—
W–AlN (HMVF)	1	0.025	0.50/210	0.15/360
W–AlN (LMVF)	1	0.025	0.50/210	0.15/360
AlN	1	0.08	0.50/220	—

Table 8. Solar performance and layer thicknesses of deposited W–AlN cermet solar selective films.

Film	α	ε_n at 20 °C	ε_n at 350 °C	Thickness (nm) (AlN/W–AlN(LMVF)/W–AlN(HMVF)/Al)
F308W3	0.93	0.03	0.08	76/30/63/200
F314W1	0.92	0.03	0.07	68/50/46/200
F317W1	0.94	0.04	0.09	64/72/48/200
F317W1v[a]	0.94	0.04	0.09	

[a] v for baked in a vacuum at 500 °C for 1 h.

the most M metal sublayers. However, for the W–AlN cermet solar coatings, the measured reflectance spectra of two sputtered tungsten films with and without 0.025 Pa nitrogen partial pressure at a total pressure of 1 Pa are nearly identical, which indicates that the nitrogen content is negligible in W sublayers. This result is consistent with those for sputtered W–N films by Shih and Dove [25].

All commercially produced solar selective coatings have a graded cermet absorber. The reflectance of the composite absorber layer is reduced by increasing the metal volume fraction, and hence refractive index, from surface to bottom [26, 27]. The graded composite films have a high solar absorptance of more than 0.90, but incur higher thermal emittance. Through fundamental analysis and computer modelling, we found a double cermet film structure of solar selective surfaces which predicted the highest photothermal efficiency [28–32]. In the double cermet layer solar coatings, solar radiation is effectively absorbed internally and by phase interference. Using this double cermet layer structure we have achieved considerably better solar performance for several deposited cermet selective surfaces than other published results. Therefore, in this study we deposited M–AlN cermet solar selective surfaces with a double cermet layer film structure. Optimized double cermet layer solar selective coatings have particular features in the reflectance spectrum; there are two points of near-zero reflectance at around 0.6 and 1.3 μm

[29, 30, 32]. The graded cermet selective surfaces do not display such features. Figure 4 also shows these features on all the measured reflectance spectra of deposited M–AlN cermet solar selective films which have the double cermet layer film structure. These two near-zero points result from optical interference effects in the double cermet selective surfaces, and are coincident with those predicted by a computer modelling calculation for several other cermet selective surfaces.

Thermal stability is another important property of solar coatings. Initial experimental results suggest that these SS–AlN cermet solar coatings should be stable at 300–400 °C in a vacuum. The W–AlN cermet materials are expected to have very good thermal stability in vacuum at high temperatures considering the high melting point of W metal (3380 °C) [33], and high decomposition temperature of AlN ceramic (>2400 °C). This performance has been initially confirmed. The reflectance spectra for the W–AlN cermet solar selective films baked at 500 °C in a vacuum for 1 h are nearly identical with those as-deposited. In order to improve further the thermal stability of these solar selective coatings at high operating temperature, a copper or molybdenum metal infrared reflection layer may be employed, instead of the Al metal layer. It is also possible to deposit a metallic tungsten layer as the infrared reflection layer by running the tungsten target in pure argon gas. Such solar coatings with film structure AlN/W–AlN/W should be stable at even higher temperature.

The M–AlN cermet solar selective coatings may be deposited onto batches of tubes using a cylindrical d.c. magnetron sputter coater. Figure 5 shows a cross-sectional schematic diagram of a commercial-scale cylindrical d.c. magnetron sputter coater. This coater may have similar mechanical structures to those developed for the production of SS–C cermet solar collector tubes [10, 14], but with different operating and physical functions. The coater contains two cylindrical post-cathodes, consisting of Al and M metallic tubes. During the deposition of the M–AlN cermet layer, both the Al and M metallic targets are run simultaneously in the argon and nitrogen gas mixture. The nitrogen partial pressure is set to be high enough to ensure that the AlN sublayer is deposited by d.c. reactive sputtering. By tube planetary rotation, a multisublayer system consisting of alternating M metallic and AlN ceramic sublayers is deposited onto the surrounding tubes. Each sublayer thickness can be controlled by Al and M metal target currents, as well tube rotation speed. This deposited multisublayer system can be considered as a macrohomogeneous M–AlN cermet layer. Varying the M target current may achieve different metal volume fractions in the cermet layers. To improve the performance, a copper, or molybdenum, metal infrared reflection layer may be employed instead of the aluminium metal layer. In this case a third Cu, or Mo, target, separated from both Al and M targets, may be installed in the vacuum chamber. Recently, the SS–AlN cermet solar coatings have been successfully deposited onto batches of tubes using a commercial-scale cylindrical d.c. magnetron sputtering coater. Detailed experimental results using this commercial-scale coater have been submitted for publication [34].

4. Conclusions

Metal–AlN cermet solar selective coatings have been deposited by a novel d.c. magnetron sputtering technology. The M–AlN cermet layer was deposited by simultaneously running both an Al target and an M metallic target in a gas mixture of argon and nitrogen. Stainless steel, $Ni_{80}Cr_{20}$, molybdenum-based alloy TZM and tungsten were used as the M metallic target. Aluminium nitride was used as the ceramic component. A nitrogen partial pressure of 0.020–0.025 Pa was chosen to ensure that a nearly pure AlN ceramic sublayer was deposited by d.c. reactive sputtering at a sputtering gas pressure of 0.8–1 Pa. SS, NiCr, TZM and W have excellent nitriding resistance; therefore, under these sputtering conditions an M metallic sublayer is deposited by d.c. sputtering. By substrate rotation, a multisublayer system, consisting of alternating AlN ceramic and M metallic sublayers, was deposited. This multisublayer system can be considered as a macrohomogeneous M–AlN cermet layer.

M–AlN cermet selective surfaces with a double cermet layer structure, AlN/M–AlN(LMVF)/M–AlN(HMVF)/Al, were deposited. An Al infrared reflector layer was first deposited on a glass substrate in pure argon gas at a pressure of 0.1 Pa. Then high metal volume fraction and low metal volume fraction M–AlN cermet layers were deposited in succession in a gas mixture of argon and nitrogen. Finally,
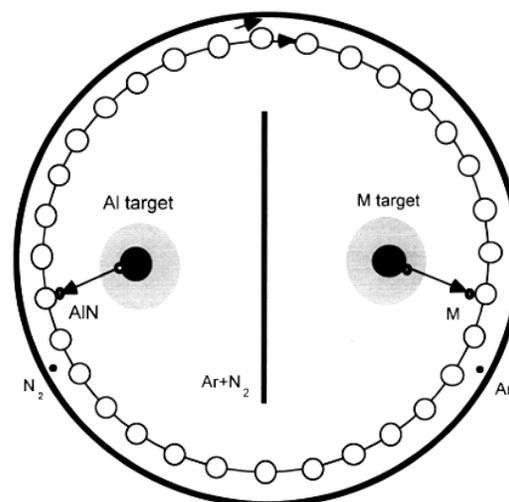

Figure 5. A cross-sectional schematic diagram of a commercial-scale cylindrical d.c. magnetron sputter coater for the deposition of M–AlN cermet selective surfaces onto tubes. The two cylindrical post-cathodes consist of an aluminium tube and another metal tube which are separated by a screen to prevent cross-contamination. The reactive nitrogen gas inlet is located at the side of the Al target and near the wall. The argon gas inlet is located at the side of the M target. The M–AlN cermet solar coatings are deposited onto the surrounding tubes by tube planetary rotation.

an AlN antireflection layer was deposited on the low metal volume fraction cermet layer by d.c. reactive sputtering at a nitrogen partial pressure of 0.06–0.08 Pa. A solar absorptance of 0.92–0.96 and normal emittance of 0.03–0.05 at room temperature and 0.07–0.10 at 350 °C have been achieved for M–AlN cermet selective surfaces.

Acknowledgments

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