Solar Energy Materials & Solar Cells 141 (2015) 337–340

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Improving the optical properties of switchable mirrors based on Mg–Y alloy using antireflection coatings

Y. Yamada*, S. Kitamura, M. Miura, K. Yoshimura

National Institute of Advanced Industrial Science and Technology (AIST), Anagahora 2266-98, Shimoshidami, Nagoya, Moriyama-ku 463-8560, Japan

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
19 May 2015
Accepted 4 June 2015
Available online 23 June 2015

Keywords:
Switchable mirrors
Mg–Y alloys
Antireflection effect
Visible transmittance
TiO_2

To improve the transmittance of Mg–Y based switchable mirrors in the transparent state the surface was coated with a TiO_2 thin film using e-beam evaporation and the optical properties were studied. The TiO_2 films had a refractive index of ~2.1. As a result of the TiO_2 coating with a thickness of ~65 nm, the transmittance in the visible range was considerably improved and consequently the visible transmittance in the transparent state reached 68%. This result was consistent with simulation results calculated using complex refractive indices for hydrides of Pd, Mg–Y alloy, and Ta. Thus, it is concluded that TiO_2 is one of the best candidates for an antireflection layer to improve the optical properties of switchable mirrors.

1. Introduction

Metal hydride switchable mirrors, which were discovered by Huiberts et al. can transform their optical properties reversibly between reflective and transparent states owing to hydrogenation and dehydrogenation [1]. Because these mirrors can control the optical transmittance in the visible and near infrared wavelength regions by changing their optical reflectance, they are of great interest as the switchable glazing in smart windows, which contribute to saving energy for air-conditioning by blocking the solar radiation through windows [2].

Mg–Y alloys ($Mg_{1-z}Y_z$) are among the most promising materials for switchable mirrors because these mirrors with the Y composition of $z>0.5$ have a high switching durability of over 10,000 cycles between the reflective and transparent states [3]. However, the transmittance in the transparent state was ~35% and the dynamic range between the two states was ~20%, which are too low for window applications. To improve the optical properties, the thickness of the Pd layer was decreased because Pd does not change its optical properties much owing to hydrogenation, that is Pd hydride shows an opaque metallic appearance, although the hydride of the Mg alloy shows a transparent appearance. By decreasing the thickness from 7.5 to 4 nm the transmittance in the transparent state increased to ~45%. The switching durability, however, sharply decreased to less than 100 cycles [4]. Furthermore a mirror with only 3 nm Pd never changed because Pd and Mg–Y interdiffused and alloyed, which eliminated the catalytic effect [4]. Thin Ta intermediate layers were then inserted between the Mg–Y alloy and Pd layers to prevent Pd from diffusing into the Mg–Y layer. Such Ta inserted switchable mirrors covered with thin Pd of 3 nm improved the optical properties without degradation in switching durability [5]. Because for south facing windows in Japan the amount of solar radiation through the windows in the winter is much larger than that in the summer due to the difference in incident angle of the sunlight. When using high-shading solar control windows southerly, the increase in heating load in the winter is larger than the decrease in cooling load in the summer. Therefore, switchable optical properties, such as high transmittance of ~70% in the transparent state and a large dynamic range between the reflective and transparent states are necessary for window applications to reduce the total load of cooling and heating [6]. Furthermore, by applying switchable mirrors with the above properties to windshields of cars, it would be possible to suppress discomfort of hot air after parking in the summer using the reflective state, and also possible to reduce consumption of fuel due to air-conditioning.

Therefore, in this study we have demonstrated that it is possible to improve the optical properties by coating antireflection (AR) layers on the surfaces of the prepared switchable mirrors.

2. Experimental

Switchable mirrors, which were composed of three layers of Mg–Y, Ta, and Pd, were prepared on glass or polycarbonate substrates. These

* Corresponding author. Tel.: +81 52 736 7474; fax: +81 52 73 7406.
E-mail address: yasusei-yamada@aist.go.jp (Y. Yamada).

http://dx.doi.org/10.1016/j.solmat.2015.06.006
0927-0248/

three layers were sequentially deposited without breaking the vacuum using direct-current (dc) magnetron sputtering of metal targets of Mg (99.99%), Y (99.8%), Ta (99.99%) and Pd (99.99%). The Mg–Y layer was prepared using co-sputtering of Mg and Y targets and the composition of the alloys was adjusted to be $Mg_{0.4}Y_{0.6}$ by controlling the sputtering power ratio of Mg to Y targets from our previous study [3]. The thickness of each layer was designed to be 50, 2, and 3 nm, respectively. Titanium dioxide (TiO_2) as AR layer was deposited using e-beam evaporation, which was carried out at JEOL Ltd., on the prepared Mg–Y switchable mirrors in our laboratory. The details of the deposition conditions of the switchable mirrors are described elsewhere [3].

The optical transmittance and reflectance spectra of the prepared switchable mirrors were measured at wavelengths between 200 and 2500 nm using an Hitachi High-Technologies U-4100 spectrophotometer.

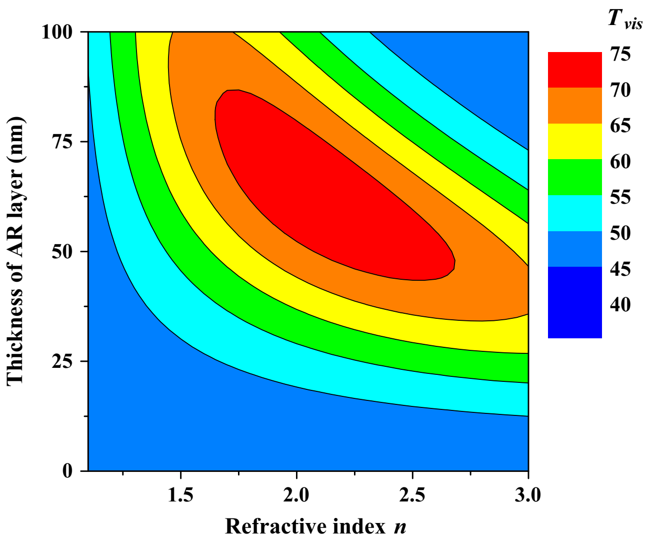

Fig. 1. Contour plot of the calculated T_{vis} values of AR coated switchable mirrors composed of $Mg_{0.4}Y_{0.6}H_x$, Ta, and $PdH_{1-\delta}$ in the transparent state as a function of refractive index and thickness of the AR layer. For the calculation we assumed the following conditions: (1) For the AR layer, the refractive index n was constant and the extinction coefficient κ was zero in the visible range; (2) the thicknesses of the $Mg_{0.4}Y_{0.6}H_x$, Ta, and $PdH_{1-\delta}$ layers were 50, 2, and 3 nm, respectively; (3) the complex optical indices of $Mg_{0.4}Y_{0.6}H_x$ and $PdH_{1-\delta}$ layers were the evaluated values from the previous study [5] and those of Ta were the reference values [6]; (4) the refractive index n and the thickness of the substrate were 1.5 and 1 mm.

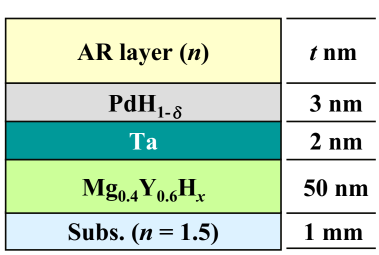

Fig. 2. The layer structure to calculate T_{vis} values of AR coated switchable mirrors in the transparent state.

3. Results and discussion

3.1. Estimation of suitable refractive index and the thickness of AR layer for high T_{vis} in the transparent state

According to the results of spectroscopic ellipsometry, the hydride of Mg–Y alloy is a dielectric material with a refractive index of between 2.3 and 2.7 in the visible range, while the hydride of Pd shows metallic properties [7]. These two layers of the hydride switchable mirror resemble the simplest structure of a low emissivity (low-e) glass (e.g. ZnO/Ag/ZnO) without a top dielectric layer: the refractive index of ZnO is ~2. We have thus attempted to improve the optical properties of Mg–Y switchable mirrors using an AR layer. To examine the effect of the AR layer in the visible range, we evaluated the visible transmittance (T_{vis}), which is an important parameter for window applications, using the following equation;

$$T_{vis} = \frac{\sum_{\lambda} D\lambda \cdot V\lambda \cdot T(\lambda)}{\sum_{\lambda} D\lambda \cdot V\lambda} \quad (1)$$

where $D\lambda$ is the spectral distribution of standard illuminant D65 defined by the International Commission on Illumination (CIE), $V\lambda$ is the CIE standard luminosity factor of the human eye, $T(\lambda)$ is the optical transmittance value at a wavelength of λ from 380 to 780 nm. Fig. 1 shows the contour plot of the calculated T_{vis} values of AR coated switchable mirrors composed of $Mg_{0.4}Y_{0.6}H_x$, Ta, and $PdH_{1-\delta}$ in the transparent state as a function of refractive index and thickness of the AR layer.

For the calculation we assumed the following conditions: (1) For the AR layer, the refractive index n was constant and the extinction coefficient κ was zero in the visible range; (2) the thicknesses of the $Mg_{0.4}Y_{0.6}H_x$, Ta, and $PdH_{1-\delta}$ layers were 50, 2, and 3 nm, respectively; (3) the complex optical indices of $Mg_{0.4}Y_{0.6}H_x$ and $PdH_{1-\delta}$ layers were the evaluated values from the previous study [7] and those of Ta were the reference values [8]; (4) the refractive index n and the thickness of the substrate were 1.5 in the visible range and 1 mm. The layer structure to calculate T_{vis} values was shown in Fig. 2. As a result of the simulation, it was indicated that a switchable mirror covered with AR layer with then value of ~2.1 and thickness of ~60 nm would improve T_{vis} to

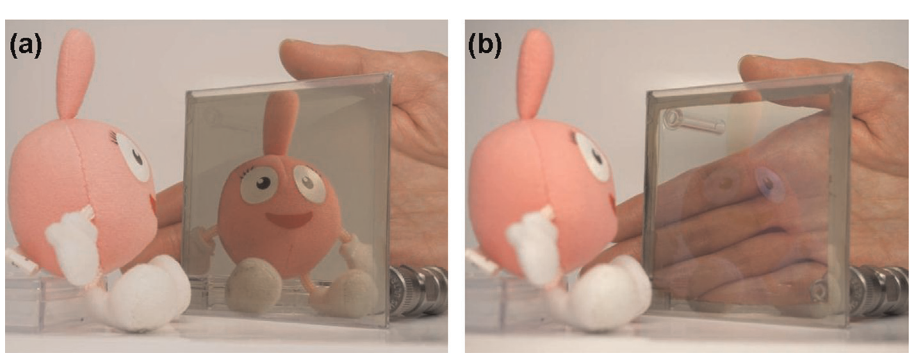

Fig. 3. Photographs of a typical switchable mirror with the AR layer in the reflective (a) and transparent (b) states.