Optical Properties of Front and Second Surface Silver-Based and Molybdenum-Based Mirrors

Houda Ennaceri, Abdelilah Benyoussef, Ahmed Ennaoui, and Asmae Khaldoun

***Abstract*—The solar reflectors used in Concentrated Solar Power (CSP) technologies are either front-surface or second-surface mirrors. The advantage of second-surface mirrors over front-surface mirrors is due to the fact that the reflective layer in second-surface mirrors is covered from the front-side by glass, which allows protection against degradation factors and aggressive outdoor conditions. In this work, front surface mirrors and second-surface mirrors were prepared based on two reflective layers (Silver and Molybdenum). A comparison between the optical properties of the two mirrors' architectures was conducted using a Perkin Elmer LAMBDA 950 UV/Vis/NIR Spectrophotometer. The results show that first-surface mirrors top-protected with amorphous Aluminum Oxide (1µm thick) layer show a higher specular reflectance compared to second-surface mirrors, which makes Al_2O_3-top-protected front-surface mirrors the best candidate in CSP application. The deposition of the Al_2O_3 layer was conducted using the Ion Layer Gas Reaction (Spray-ILGAR) technique, which did not alter the optical properties of the unprotected mirrors, conserving a high specular reflectance of the Silver-based first-surface mirrors (94% in the Near Infrared range).**

***Index Terms*—Aluminum oxide, front-surface mirrors, molybdenum, protective layer, second-surface mirrors, silver, specular reflectance.**

I. Introduction

In Concentrated Solar Power (CSP) technology, reflectors or mirrors are the most important components. There are two types of solar mirrors used in CSP applications: first-surface glass mirrors, where the light beam is reflected on top of the reflective layer, and second-surface glass mirrors, where the light beam goes through the glass before being reflected on the reflective layer as illustrated in Fig. 1.

The current Concentrated Solar Power (CSP) reflectors have a specular reflectance of 93% to 94% with an expected life time ranging from 20 to 25 years [1]. In second-surface mirrors, the reflective coating is applied to the back surface, and is therefore protected from potential damage and degradation due to the aggressive outdoor conditions. On the other hand, the durability of first-surface mirrors without top-protective coatings is seriously affected by degradation factors such as abrasion, oxidation, corrosion, and soiling [2]. Nano-coating of first-surface reflectors is a promising option to maintain their durability without altering their specular reflectance [3].

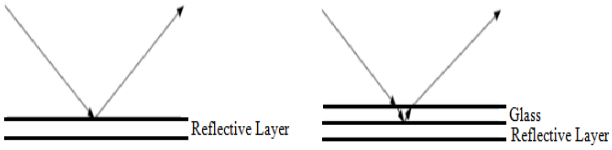

Fig. 1. First-surface mirrors (left) versus second-surface mirrors (right).

In this study, both front-surface and second-surface CSP mirrors are prepared based on both Silver and Molybdenum as the reflective layer in order to compare their optical properties of first surface mirrors with and without the top-protective coating, and second-surface mirrors. The architecture followed in the preparation of the Silver-based front-surface mirrors is illustrated in Fig. 2

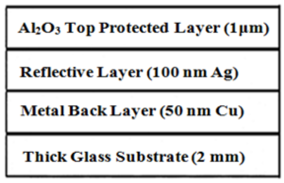

Fig. 2. First-surface Silver-based mirrors architecture.

The architecture followed in the preparation of Ag-based second-surface mirrors is illustrated in Fig. 3. Both types of mirrors are protected by a Copper back layer from the rear side in order to prevent the oxidation of the reflective layer surface.

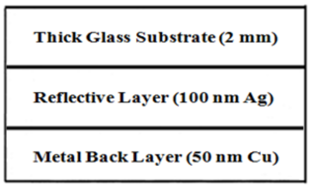

Fig. 3. Second-surface Silver-based mirrors architecture.

The choice of Aluminum Oxide (Al_2O_3) as a top-protective layer for front-surface mirrors is based on its hardness, stability and transparency [4].

The preparation of first-surface and second-surface Molybdenum-based mirrors was conducted using the same architecture illustrated in Fig. 2 and Fig. 3, replacing the

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reflective layer of Ag by Mo with the same thickness (100 nm).

II. Experimental Procedure

A. Materials and Methods

The Acetone/Ethanol cleaning method was used to clean glass substrates of 25×25×2 mm dimensions. The method consists of immersing the samples in a first stage in Acetone (99.998%) for 5 minutes with ultra-sonication, the samples are then cleaned with distilled water and dried with Nitrogen.

In the second stage, the glass samples are cleaned with Ethanol (99.998%) following the same procedure. The samples are then directly immersed in high resistance water (18.2 mΩ) for 5 minutes with ultra-sonication, and next dried with Nitrogen.

Pure Silver, Copper and Molybdenum were used for the deposition of the reflective layers (Silver and molybdenum) and metal back layer (Copper), respectively. After the preparation of the mirrors using Physical Vapor Deposition (PVD-Sputtering), a protective layer of Al203 was deposited on the surface of the Silver layer/Molybdenum by mean of the Ion Layer Gas Reaction (Spray-ILGAR).

The precursor solution for the deposition of the Aluminum Oxide layer was prepared by dissolving Aluminum 2, 4-Pentanedonate, 99% (from Alfa Aesar) in Ethanol p.a. and deionized water.

Aluminum Oxide (Al_2O_3) was deposited using the Ion Layer Gas Reaction (Spray-ILGAR) method [5] at temperature of 500 ℃, with Nitrogen (carrier gas) flow rate of 5L/min, and a solution rate of 100 ml per 60 minutes.

B. Phase and Chemical Composition

The XRD spectrum shows that the deposited layer by ILGAR at 500 ℃ is amorphous. As shown in Fig. 4, no significant peaks were identified except the broad peak due to the glass substrate.

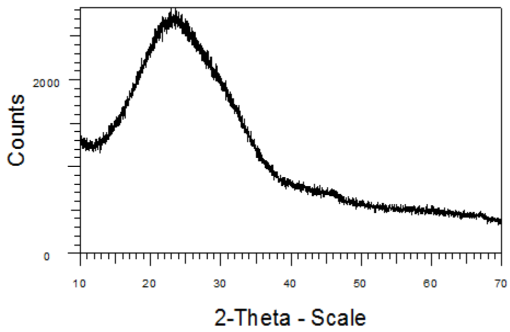

Fig. 4. XRD Spectrum of as-deposited Amorphous Al_2O_3 film on glass substrate.

The chemical characterization of the samples was conducted using Energy Dispersive X-Ray analysis (EDAX), and shows 47.75 at % Al and 50.71 at % O. The carbon contamination is present in the samples with 1.53 at % C.

III. Results and Discussions

A. Spectrophotometric Measurements

The spectrophotometric measurements of the different layers were conducted using a Perkin Elmer LAMBDA 950 UV/Vis/NIR Spectrophotometer. The reflectance of the Copper (50 nm), Silver (100 nm), Molybdenum (100nm) and Aluminum Oxide (1 μm) layers are presented in Fig. 5

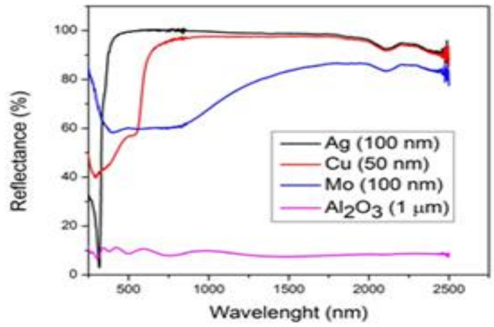

Fig. 5. Reflectance of the Different layers (Ag, Cu, Mo and Al_2O_3) deposited on glass

The absorptance of the different layers of Cu, Ag, Mo and Al_2O_3 deposited on glass is illustrated in Fig. 6

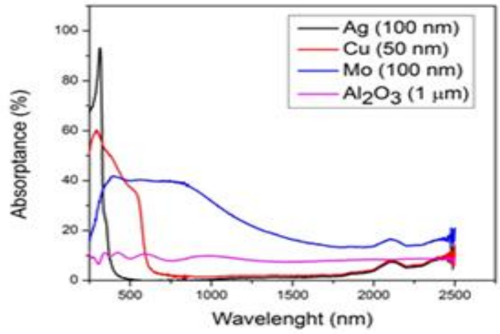

Fig. 6. Absorptance of the Different layers (Ag, Cu, Mo and Al_2O_3) deposited on glass

The reflectance, absorptance and transmittance are related using the following formula:

$$R+T+A=100 \quad (1)$$

The amorphous Aluminum Oxide layer deposited by mean of Spray-ILGAR technique showed a high transparency (86% transmittance), which makes it a good candidate for top-protective coating of first-surface CSP mirrors.

As illustrated in Fig. 7 and Fig. 8, second-surface mirrors show lower specular reflectance compared to the front-surface mirrors, and that for both Silver-based and Molybdenum-based mirror combinations.

In the visible range and the Near-Infra-Red (NIR) range (400-2200 nm), the specular reflectance of the first-surface Ag-based mirrors is 98.6%. On the other hand, as can be noticed from Fig. 8, the first-surface Mo-based mirrors have a lower specular reflectance (79.4% average reflectance in the near infrared range and 61.6 % average reflectance in the visible range) compared to the Silver-based mirrors.

The Aluminum Oxide (Al_2O_3) layer was deposited on top of the Silver-based and Molybdenum-based first-surface mirrors. The spectrophotometric results show that the specular reflectance of the Mo-based first surface mirrors decreased with the deposition of the Al_2O_3 top protective layer (72.2% reflectance in the Near Infrared and 40.2%

reflectance in the visible range) as illustrated in Fig. 10. The interference pattern of the ($Cu+Mo+Al_2O_3$) in the visible range is an index of the homogeneity of the layer.

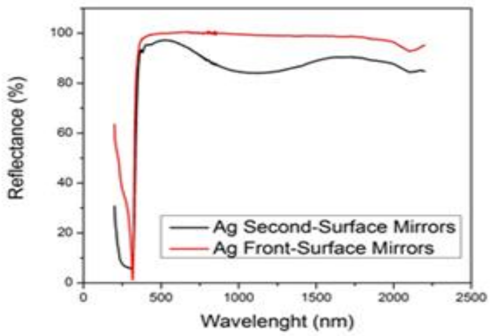

Fig. 7. Ag-based first-surface and second-surface mirrors

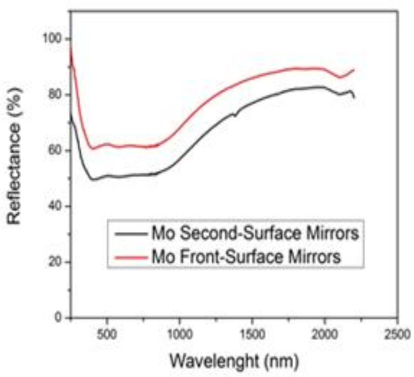

Fig. 8. Mo-based first-surface and second-surface mirrors.

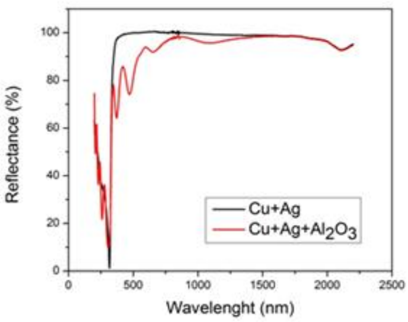

Fig. 9. Specular reflectance of ($Cu+Ag+Al_2O_3$) first-surface mirrors.

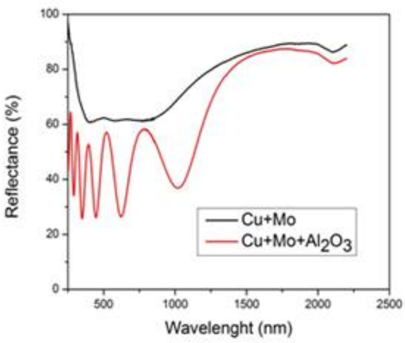

Fig. 10. Specular reflectance of ($Cu+Mo+Al_2O_3$) first-surface mirrors.

The results of this study show that the Al_2O_3 top-protected mirrors exhibited the highest specular reflectance compared to the second-surface mirrors. For Silver-based mirrors, the spectrophotometric measurements show that the unprotected front-surface mirrors have a high specular reflectance of 98.6% compared to second-surface mirrors (88.77% reflectance). On the other hand, the deposition of the amorphous Al_2O_3 top-protective layer on the surface of the Ag-based front-surface mirrors resulted in a specular reflectance of 94% in the Near Infrared range and a decrease in the visible range (87.5% average reflectance). For Molybdenum-based mirrors, the unprotected front-surface mirrors exhibited a specular reflectance of 79.4% in the Near Infrared range compared to second surface Mo-mirrors (70.34% reflectance in the Near Infrared). The Al_2O_3-protected Mo-front-surface mirrors showed a specular reflectance of 72.2% in the Near Infrared range and a significant drop in the visible range (40.2% reflectance).

All in all, the deposition of the Aluminum Oxide (Al_2O_3) layer by Spray-ILGAR technique conserves a high specular reflectance of the CSP mirrors (94% in the Near Infrared) compared to second-surface mirrors (88.77% reflectance), which is in good agreement with the results of the Advanced Solar Reflective Mirrors prepared by NREL using IBAD deposition technique for the Aluminum Oxide protective layer [6].

IV. Conclusion

In Concentrated Solar Power (CSP) application, the choice of second-surface mirrors over first-surface mirrors is based on their hardness and durability properties due to their glass-front-side, which ensure the protection of the reflective layer form different degradation factors.

The results of this study is are summarized in Table I and Table II, and show that the deposition of the Aluminum Oxide top-protective layer by mean of the Ion Layer Gas Reaction (Spray-ILGAR) conserved a high specular reflectance of the Silver-based first-surface mirrors (94% in the Near Infrared range). Therefore, Silver-based first-surface mirrors top-protected with Aluminum Oxide from the front side represent the best candidate since their specular reflectance is higher than the Silver-based second-surface mirrors.

TABLE I: Spectrophotometric Measurement of the Prepared First-Surface Mirrors

First-Surface Mirror Type	Specular Reflectance (400-2200 nm)
Cu + Ag	98.6%
Cu + Ag + Al_2O_3	94% (NIR) – 87.5% (VIS)
Cu + Mo	79.4% (NIR) – 61.6% (VIS)
Cu + Mo + Al_2O_3	72.2% (NIR) – 40.2% (VIS)

TABLE II: Spectrophotometric Measurement of the Prepared Second-Surface Mirrors

Second-Surface Mirror Type	Specular Reflectance (400-2200 nm)
Second Surface (Ag + Cu)	88.77%
Second Surface (Mo + Cu)	70.34% (NIR)

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Houda Ennaceri was born in Morocco. She is currently conducting her PhD research in physics of materials at University Mohammed V-Agdal, Rabat 10000, Morocco, and holds a master's degree in sustainable energy management in (MSSEM) from Al Akhawayn University in 2013, and a bachelor's degree in engineering and management Science (BSEMS) from Al Akhawayn University in 2010. Houda Ennaceri also participated in an exchange program in engineering management in Montana State University (MSU, Bozeman, USA) in 2009.

Ms. Ennaceri is currently working on the InnoTherm II research project "Nanocoating and testing: A step towards the improvement of CSP reflectors for less intensive maintenance both in terms of labor and water", which consist on the nano-coating and testing of CSP reflectors in order to improve their efficiency and durability without altering their specular reflectance. The research of Ms. Ennaceri includes the development of new hydrophobic coating materials that are more durable, energy efficient and more cost-effective, which would minimize the use of water for cleaning the CSP mirrors.

Ms. Ennaceri has been awarded the DAAD scholarship under the sandwich model to conduct different experiments within the Helmholtz Zentrum Berlin für Materialien und Energie (HZB). She has also been awarded the participation in the enerMENA internship on Concentrated Solar Power (CSP) at the Plataforma Solar de Almeria.