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Astronomical mirror coating using magnetron sputtering

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ABSTRACT

Reflective coatings on large astronomical mirrors have been predominately done using aluminum evaporation techniques, but the high reflectivity and low emissivity properties of silver makes this an attractive material choice for demanding visible and infrared mirror applications. Multilayer silver deposition using magnetron sputtering is a newer concept in large mirror applications involving increased technical and financial risk. Recently a vacuum system that was used to coat a 3.5 m telescope mirror using aluminum evaporation was modified to sputter coat a multilayer silver stack. In this paper, we present the hardware configuration required to effectively sputter coat a multilayer silver-based coating. Critical design and process challenges will be presented, and solutions will be described. Different overcoat layers have been developed to achieve high reflectivity and to protect silver mirrors from tarnish and corrosion. The effects of such layers were understood and optimized based on optical properties and environmental durability testing. Temperature measurements were performed on a simulated mirror section. The 3.5 m mirror was successfully coated with the silver-based coating in September 2019.

INTRODUCTION

Large telescope mirrors have been traditionally coated with aluminum using filament evaporation. This technique has been a well proven method for astronomical mirrors. Aluminum has been the most used material in mirror coating applications. Aluminum mirror finish has high reflectance in the 200-400 nm and the 3000-10000 nm wavelength range compared to most other metals. The reflectance is slightly lower in the 400-3000 nm wavelength range compared to silver and few other materials. Aluminum naturally reacts with air creating a barrier oxide layer reducing nominal reflectance. Although this barrier layer provides some protection of the reflector layer against environmental effects, this protective layer can be susceptible to environmental conditions and can degrade rapidly over time affecting the reflectivity of the mirrors. This increases the frequency of mirror recoating. Extending the coating lifetime has many benefits including minimizing telescope functional downtime and cost. Adding protective layers over the aluminum films is known to increase the durability of these films protecting them from the dusty and humid environment and extending the lifetime of the coatings. However, adding layers on the reflective film compromised reflectivity and demanded using a more complicated coating system to deposit the various layers. Despite the slightly lower reflectance and durability, for non-critical applications, pure aluminum coating is the most preferred coating technology. This is because, the cost benefits of bare aluminum coatings significantly outweigh the marginal reflectance improvement in visible spectrum.

For critical applications, other materials and coating technologies have been opted to achieve desired results. Silver has high reflectivity and low emissivity; hence this is one of the preferred reflectance materials for the most demanding visible and IR mirror applications. However, silver has poor adhesion properties to most mirror substrates and tarnishes when exposed to various environmental conditions. Additional layers were added to improve adhesion and minimize corrosion effects. Wolfe et al. developed a film stack where SiNx was used as a protective layer to minimize corrosion effects. A thin layer of NiCrNx was used between the silver and SiNx layer. This is used to provide better adhesion and nucleation sites for the development of a dense SiNx layer [1]. NiCrN reduces the porosity in the SiNx layer thus decreasing the permeability of the corrosive species through the protective layer and reacting with the silver. This helps in minimizing the corrosive effects [2]. Although, this interlayer improves the durability of the films, it reduces the reflection, especially in the blue region. A 6-8 Å NiCrNx is proven to be optimal for best reflectivity and durability. A thin layer of NiCrN is also used between the mirror substrate and silver to improve adhesion of the silver reflector layer to the substrate. Mirror coatings at the Gemini Observatory uses a stack of 65 Å of nickel chromium (NiCr),1100 Å of silver (Ag), 6 Å of NiCr, and 85 Å of Si_3N_4 [3]. Similar coatings will be used in this paper.

HISTORY AND UPGRADE

The original coating system was built in 2006 for depositing aluminum using filament evaporation process. However, the evolution of CubeSats and their reduced cross-section required a film stack with improved reflectance in the visible and IR wavelength regimes. This demanded a protected silver coating. Hence in 2017 the system was converted from filament evaporation to sputtering.

The vacuum chamber assembly is a vertical bell jar configuration. This comprised of a main vacuum chamber, base-carriage assembly, mirror support structure, and chamber lift mechanism. The chamber is roughly 3.96 m in diameter and 2.43 m tall. The main chamber can be raised off the base-carriage using motorized jackscrews. The main chamber assembly serves as the housing for deposition sources, pumping systems, valves, and other accessories. The base-carriage assembly can be translated under the main chamber on a rail system, and this houses the mirror support. The mirror support structure is designed as whiffletree setup. The fixture has multiple arms with an articulating 3-point whiffletree at each location. Disks with PTFE pads are mounted to the end of each arm to align with the mirror pads epoxied to the backside of the mirror. The fixture was designed to ensure that the load of the mirror was evenly distributed.

A multi-stage pumping system pumped the chamber from atmospheric pressure to the 10^{-7} mbar region. It was designed to provide maximum pumping efficiency and reliability to handle process gas loads. The roughing system evacuates the chamber to high vacuum cross-over pressures in approximately 25-30 minutes. High vacuum pumping was achieved using cryopumps and LN2-cooled Meissner coil. A representative pump down curve is shown in Fig. 1.

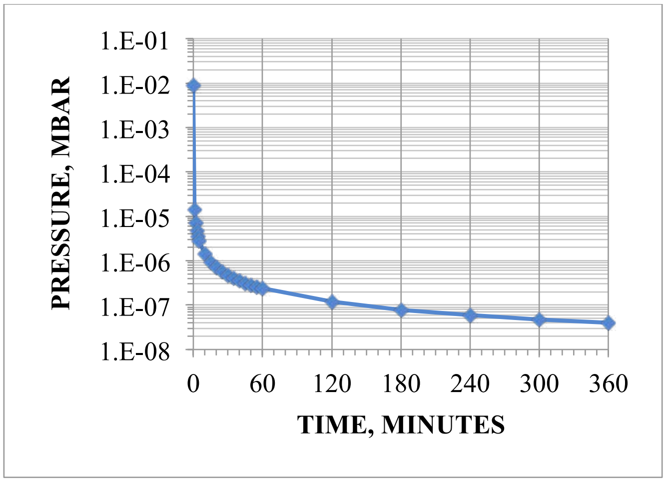

Figure 1. High vacuum pumpdown

An oxygen glow discharge system was provided to clean the mirror prior to deposition. The glow discharge system consists of a DC power supply, aluminum rod electrode and shield within the chamber, and gas flow control system. The glow discharge was typically done at 1-3 Torr pressure range. After glow discharge cleaning, the chamber pumps down to base pressure to ensure removal of residual oxygen before deposition commences.

A filament array was located above the surface of the mirror in a pattern. This array comprised of concentric rings of resistively heated filaments that are clamped to high current bus bars. A filament array shield was installed in front of the array to limit the evaporant angle of incidence and to shield the surface of the mirror from the top region of the chamber. The deposition rate is maintained at a sufficient rate to maximize reflectivity.

Evaporant shields were installed over insulators to prevent short circuits between the bus bars and the support structure.

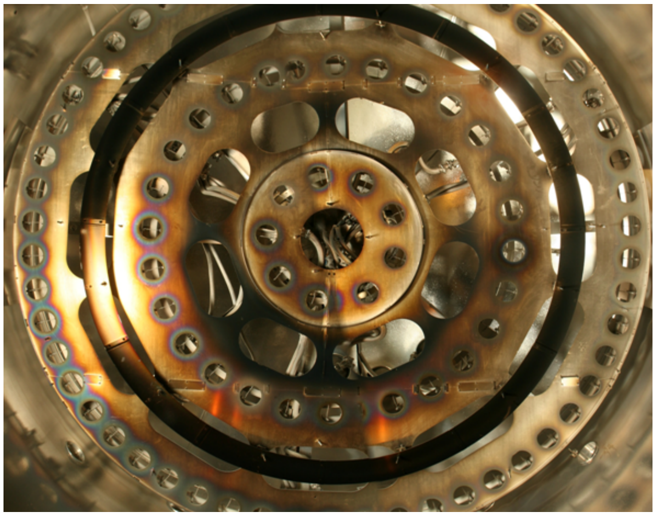

Figure 1. Filament masking system

Filaments are charged with a pre-determined amount of aluminum based on the film thickness. Thickness uniformity across the mirror was achieved by positioning the filaments in appropriate locations. An Inficon STM-3 deposition monitor with six quartz crystal sensors was used to monitor and control the deposition rate. The crystal monitor was fully integrated into the deposition control software to control the evaporation rate and thickness of the aluminum. Depending on the preference, the closed loop through the deposition controller can be bypassed and the filaments can also be charged with the exact amount Al and depleted during coating.

The mirror was loaded onto a stationary assembly located on the lower part of the chamber. The whiffletree acts as a support frame for the mirror providing it structural support.

CONVERSION TO SPUTTERING

Hardware and software modifications were made to enable the deposition of the 4-layer protected silver stack. The main hardware modifications were the deposition system to enable coating the various layers and substrate rotation to obtain uniform thickness. Appropriate software modifications were made to enable recipe creation and automated sequential deposition through the HMI and PLC.

The sputtering assembly consisted of multiple magnetron cathodes and shutter assemblies. The system was configured to deposit up to four materials, supporting deposition of both metallic, and dielectric layers. The sputtering assembly was mounted in the chamber in a static configuration, depositing down onto the mirror surface. The assembly was comprised of four support beams positioned 90° apart. Four cathode boxes were mounted on the radial beams. Each cathode box consists of a 1600 mm x 125 mm rectangular magnetron cathode, gas channels for process gases, uniformity masks and gas baffle masks. The cathode shutter was also mounted below each cathode box. A shutter assembly is provided for pre-conditioning of the cathode and for layer termination. The entire cathode box can be adjusted vertically and radially to allow fine tuning of the uniformity.

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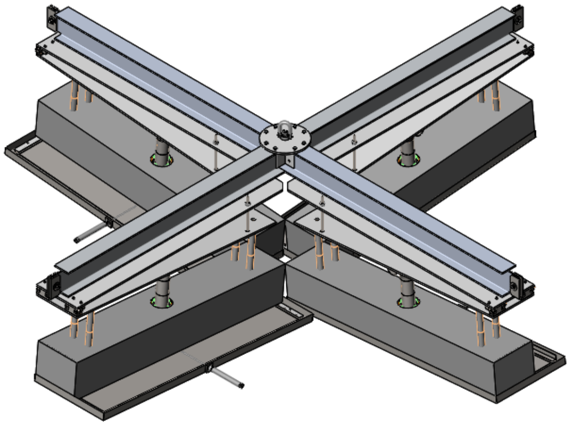

Figure 3. Sputtering module

The stationary mount used for filament evaporation was replaced with a whiffletree assembly for the sputtering process. In order, to obtain uniform coating thickness, this setup had to be rotated below the sources. This was done by adding a rotary hub and DC drive system to the existing whiffletree assembly.

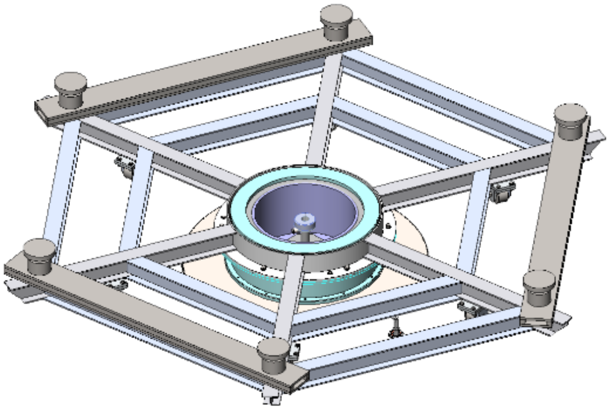

Figure 4. Mirror support system

PROCESS OPTIMIZATION AND CHARACTERIZATION

Coating on the mirror is an expensive and time-consuming process. Therefore, a detailed and thorough process optimization was done to obtain the required film properties. Process optimization was done on microscopic slides and optical grade substrates. These samples were mounted radially from the center to edge on the simulated mirror setup rails.

Film thickness and optical performance was measured using reflectometer and spectrophotometer respectively. Environmental stress testing was done in order to stress test the films under extreme harsh environmental conditions. The test conditions were chosen to closely replicate the surroundings where the telescope mirror would be located. For the environmental testing, the samples were exposed to 90% relative humidity at 30°C for 2 weeks.

For process tuning of deposition rates and thickness, crystal sensors were positioned across the radius of the mirror and process parameters were changed by observing the in-situ crystal monitor readings. This eliminated physical thickness measurements on the substrates and also expedited the process by eliminating the system pump/vent cycles. These are specifically valuable for the thin NiCrN layer thicknesses where physical measurements are unreliable.

Individual films were first run to evaluate and fine tune the thickness uniformity across the mirror and to optimize the optical properties. Based on the film thickness, the uniformity masks were adjusted to obtain the uniform thickness across the mirror radius. Furthermore, process optimization for the various process parameters (power, gas flows and substrate rotational speed) was done to achieve the required film optical properties.

Once individual films were optimized, the entire film stack was deposited. The protected silver stack consisted of 8.5 nm NiCrN (Adhesion Layer) / 110 nm Ag (reflector) / 0.6 nm NiCrN (interlayer) / 8 nm SiNx (protective layer). Reflectance of bare Al (filament evaporation) and protected silver are shown in Fig. 5.

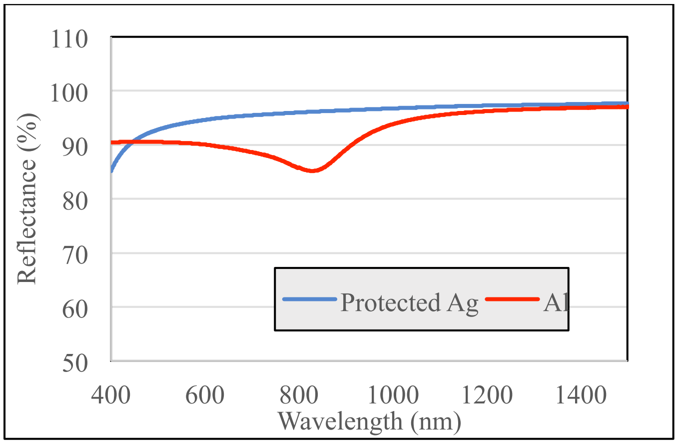

Figure 5. Optical properties: reflectance

As seen in the Fig. 5, the 4-layer protected silver stack outperforms the aluminum in the visible and IR wavelength regimes. There is a significant improvement in the reflectivity for Ag films in the 850 nm wavelength regime.

The thickness of the interlayer NiCrN and the top layer SiNx is very crucial in obtaining a durable film with good adhesion without compromising reflectivity. The optimal layer thickness for the NiCrN is estimated to be 6-8A. However, quantifying such a thin layer thickness is challenging. Two different thicknesses of NiCrN (6 A and 11 A) and SiNx (85A and 110 A) were evaluated. The thickness was controlled by magnetron sputtering power and the substrate rotation speed. The thickness and rates were monitored by the quartz crystal monitor. Reflectance and adhesion tests were performed on the film stacks with different film thicknesses, and no significant difference in performance was observed. The layers also showed negligible difference in performance in post environ-ment stress tests. A representative reflectivity plot is shown in Fig. 6.

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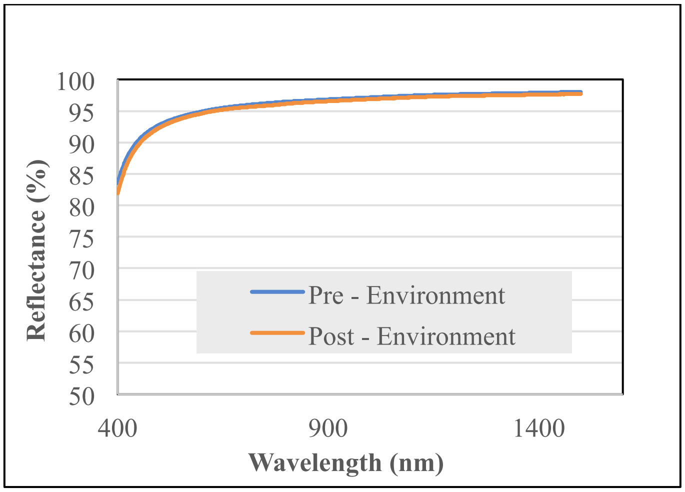

Figure 6. Environmental effects on optical properties

Mirror temperature

The sputtering process involves highly energetic ions which may induce heating of the mirror substrate. Although the heat load from sputtered particle flux is small, significant heating of the substrate is possible because of the negligible convection in the vacuum chamber. The Air Force Research Laboratories mirror is a borosilicate mirror. The material has higher coeffi-cient of thermal expansion and a lower strength, making it more susceptible to thermal damage than Zerodur or ULE [4]. Based on the mechanical properties of the mirror, it was modeled that the maximum temperature gradient is 5° C between the top/bot-tom surfaces and 10° C radially from center to edge of the mirror. To experimentally evaluate the temperature gradient on the mirror, thermocouples were attached onto 6” square blocks using epoxy. The thickness of these blocks was the same thickness as the mirror.

A 4-layer protected silver process was run, and the temperature was measured at different locations of the mirror. The temperature gradient between the top and bottom surface of mirror was negligible (<2° C) and radially the temperature gradient was <6° C. This was within the allowable temperature limitations of the mirror.

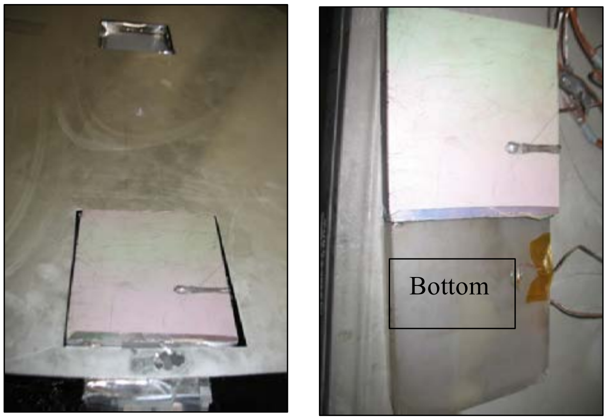

Figure 7. Temperature measurement setup

Coating of the 3.5 m mirror

Once all the process qualifications were met, the deposition was performed on the 3.5 m Air Force Research Laboratories mirror. The picture of the coated mirror is shown in Fig. 8.

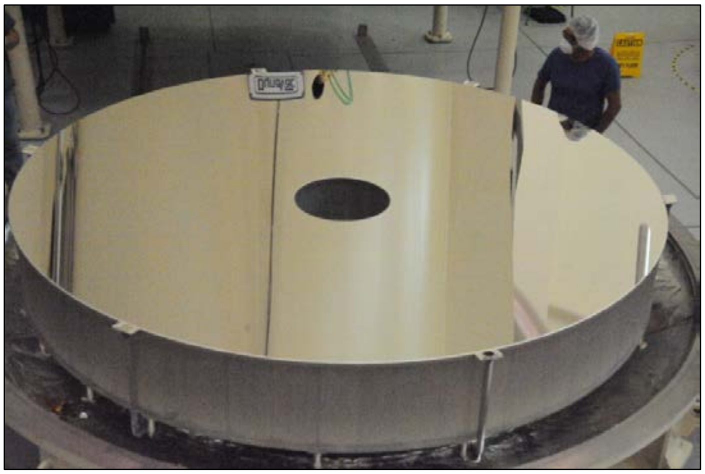

Figure 8. Coated 3.5 m mirror

Witness samples were placed along with the mirror in the telescope. These same samples are mounted next to the mirror to analyze the performance of the coating over time. The performance of the coating was tested on the samples overtime and is shown in Fig. 9. There as negligible degradation over the measured period of time.

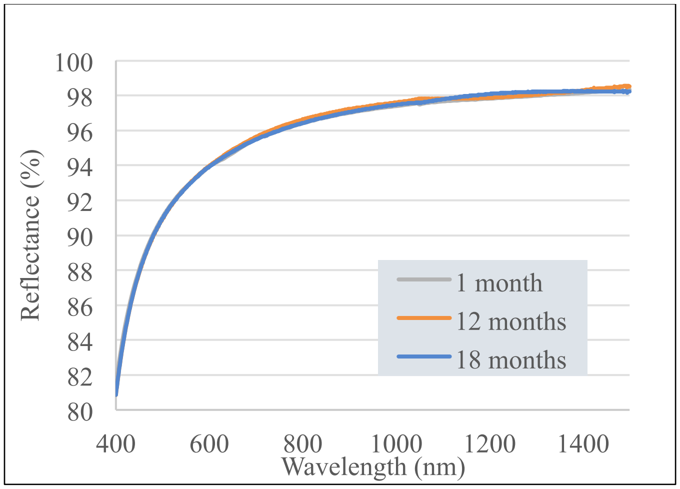

Figure 9. Performance over time on witness samples on the telescope

CONCLUSIONS

A 3.5m optical mirror aluminum evaporation system was successfully converted to a sputter deposition system to deposit a multi-layer silver stack. A highly durable 4-layer Ag stack gave high reflectance with good adhesion through process optimization. The mirror was coated in 2019 and with reflectance of $R_{average}$ (450–800 nm) > 94% and $R_{average}$ (800–1200 nm) > 97%. Over the subsequent two years, extreme

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environmental testing confirmed the optical stability and coating durability of the 4-layer protected Ag stack.

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