

Multilayer optical coatings on large telescope mirrors using magnetron sputtering

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ABSTRACT

Recent advancements in space and astronomy research have increased the demand for improved performance from large ground and space telescope mirrors. Such demands drive the need to coat these mirrors with multilayer reflective coatings with metal and dielectric layers providing durable optical films with enhanced properties. Multilayer dielectric coatings are generally challenging, demanding complex hardware and process controls. Coating such films on large telescope mirrors is still in the early stages of understanding the intricacies of system and process design. Critical system setup and methods to overcome process variations over the long coating duration will be discussed in this paper. Hardware design challenges including cathode positioning, mask optimization, shutter reliability will be evaluated. Prevalent issues with hidden anodes and particulates will be addressed and methods to minimize these effects will be detailed.

INTRODUCTION

System Configuration

The mirror coating system (Figure 1) is configured as a vertical bell-jar assembly. The system features a top and base assembly and chamber lift mechanism. The top shell can be raised off the base-carriage using motorized jackscrews and the base-carriage assembly can be moved back and forth under the top shell on a rail system. The top shell assembly serves as the housing for deposition sources, pumping systems, valves, and other accessories. The bottom carriage houses the mirror support system.



Figure 1 : Mirror coating System

The bottom carriage retracts to load the mirror. Once the mirror is loaded onto the mirror support system, the bottom assembly moves beneath the top shell. The top and bottom shells are sealed and evacuated using a multi-stage pumping system from atmospheric pressure to the $< 10^{-6}$ Torr region.

The pumping system is 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 is achieved using cryopumps, turbo-pumps and LN₂-cooled Meissner coil. A representative pump down curve is shown in Figure 2.

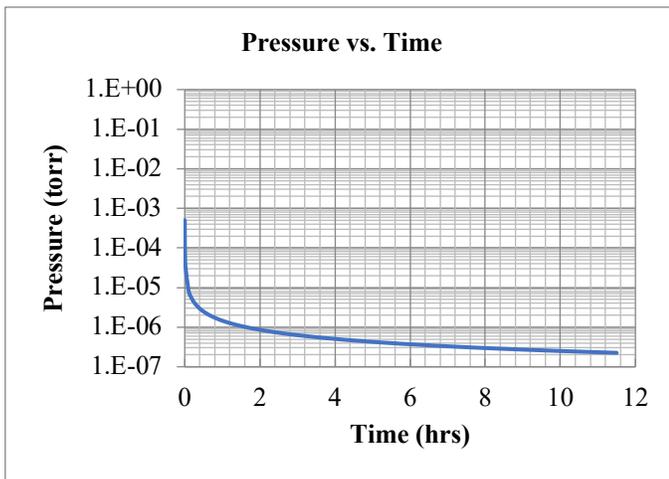


Figure 2: High Vacuum pump down

All the pumps are equipped with throttle gate valves so that the pumping conductance can be tailored to optimize the sputtering pressures. The Meissner coil provides high water vapor pumping during the mirror surface cleaning and deposition processes.

An Argon/oxygen glow discharge system is provided to clean the mirror prior to deposition. The glow discharge is typically done at 1-3 Torr pressure range. After glow discharge cleaning, the chamber pumps down to base pressure before the deposition commences. This ensures the removal of any residual oxygen that may be released from the mirror and chamber internals.

The sputtering deposition assembly is located above the surface of the mirror and 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 is mounted in a static configuration, depositing down onto the mirror surface. The assembly comprised of four cathode boxes mounted on radial support beams positioned 90° apart. Each cathode box consists of a rectangular magnetron cathode, gas channels for process gases, uniformity masks and gas baffle masks. The cathode shutter is mounted below each cathode box and is used for sputter target pre-conditioning layer termination. The entire mini chamber (cathode box and shutter) (Figure 3) can be adjusted vertically and radially to allow uniform coating of various mirrors (primary, secondary, and tertiary).

The gas baffle within the cathode box assembly typically consists of a set of nozzles delivering gas across the length of the cathode. The number and distribution of the nozzles is optimized to achieve sufficient and uniform process pressure across the cathode box. The opening of the uniformity mask placed beneath the target is optimized to achieve the required uniformity across the mirror. The shutter mounted below the cathode box is actuated by pneumatic cylinders and is used to precisely control the layer termination.



Figure 3 : Cathode Box configuration

Challenges and solutions

Deposition of thick dielectric films is challenging and deals with several concerns such as

1. Stability of the reactive sputtering process
2. Temperature of the substrate
3. Reliability of the shutters
4. Particulates

The design and configuration of the system plays a vital role in minimizing the issues and improving the reliability of the system and improving the quality of the films.

Protective dielectric coatings are typically sputtered using appropriate reactive gases (oxygen or nitrogen) along with the inert working gas (argon). Techniques used to deposit dielectric materials include direct current reactive magnetron sputtering (DCRMS), pulsed reactive magnetron sputtering (PRMS), radio frequency reactive magnetron sputtering (RF-DMS) and mid-frequency reactive magnetron sputtering (MFMS)[7][8]. Direct magnetron sputtering causes poisoning of the target material resulting in arcing and unstable process. RF magnetron process suffers from very slow deposition rate and expensive equipment cost. So, neither of these techniques are ideal for industrial thin film coatings. The two commonly used techniques are MFMS and PRMS. MFMS requires dual sputtering cathodes and operates by altering the potential of the two cathodes. PRMS is performed by pulsing the DC voltage in the 10–350 kHz range with duty cycles in the 50–90% range. This eliminates the arcing issues caused during the DMS. PRMS is a simpler and less expensive approach to meet the requirements of this project and hence is used in the current system.

Stability of this reactive process can be improved by process and system design optimization.

Reactive sputter deposition of a uniform compound film with specific composition at an optimal deposition/energy rate is a real challenge due to the hysteresis effects [3],[4]. Hysteresis causes instability in the process and results in variation in the target discharge voltage causing deviation in the mode of

operation (metal, transition, and oxide). This results in films of varying composition and deposition rates over time. The variation in the process can be minimized by eliminating/minimizing the hysteresis effect or by actively controlling the process parameters to respond to the hysteresis [[1],[5].

The best and most cost-effective means to improve the process stability is by actively controlling and reacting to hysteresis. An active feedback control was used in the system such that the partial pressures and ratios of reactive gas and argon were changed to actively maintain a constant and ideal target voltage. This resulted in > 500 kWhr of stable process and yielded stable and uniform film properties over extended periods of time.

Typically, in most sputtering systems, the grounded chamber walls act as an anode, providing a complete circuit for the plasma. During reactive sputtering, the anode (chamber walls) gets coated with dielectric material causing impedance variation and an increased discharge voltage. This results in an unstable process. The plasma extinguishes when the anode is fully coated with dielectric material, and this effect is called “disappearing anode”. The lifetime of the anode depends on its surface area and its proximity to plasma.

Impacts of disappearing anode include:

- Unstable process.
- Arcing on the sputter target causing macro-particles
- Arcing on the substrate damaging the substrate and the films.
- Unwanted temperature rise of the chamber components (masks, shutters) leading to mechanical failure.

In the current setup, the cathodes are enclosed within a mini-chamber setup, providing less anode surface area. This results in reduced anode lifetime. In addition, to the grounded walls, the mini chamber also consists of grounded masks, shields, and shutters which act as anodes drawing secondary electrons from the plasma. The high temperature of secondary electrons adversely impacts the functionality of these components. Elevated and high temperature fluctuations induce mechanical failures on shutters due to thermal expansion on the moving parts. Temperature fluctuation also leads to increased stress on the films deposited on the parts of the cathode box leading to material flaking and particles.

Hence maintaining a low and stable temperature of the mini chamber components is important for the reliability of the system. The key to maintaining stable and low temperature of the mini-chamber components is to properly channel the electrons to dedicated and effective “anode”.

An efficient anode design is vital for eliminating the “disappearing” anode issues and avoid undesired temperature concerns on the system functionality. An efficient anode extends the meantime between failures and system downtimes. The mirror coating system is configured with a “hidden” anode where the anodes are appropriately placed within the cathode box such that it is protected from the direct deposition of the coating material and provides an effective path for the

secondary electrons. The anodes can be positively biased to enhance proper channeling of the secondary electrons and to minimize traction of electrons to the chamber components. To simplify the setup and configuration, the anodes were kept at ground potential and the cathode box components were isolated from the grounded chamber walls.

The anodes are made of copper and are water cooled to minimize overheating. At least 500 kWhr of continuous and stable dielectric deposition was performed without indications of disappearing anode. In addition, the cathode box components (masks, shutters) were maintained close to room temperature during the long dielectric coatings. This eliminated hardware failures induced due to elevated temperatures such as warpage, thermal expansion, particles etc. and improves the longevity of the components.

Particles are a huge concern in any deposition especially for the sputter down configuration where the substrate is placed below the deposition system. Particles flaking from the deposition system tend to land on the substrates due to gravity. For small substrates, it is relatively easy to mount the substrate above the deposition components minimizing the risk of the particles. However, for large substrates such as telescope mirrors, it is difficult and risky to handle the substrate and its rotation above the deposition zone. Hence, it is best to do a sputter down configuration. The best way to minimize particles on the substrates is by proper shield design and a consistent preventive maintenance schedule.

The inner walls of the cathode box and its components accumulate heavy coating. Over time this material tend to flake and flaking increases if high residual and thermal stresses are present in the accumulated material.

A few commonly used techniques to minimize flaking are pasting, reducing intrinsic thermal stress on the accumulated material, proper shielding, and preventive maintenance. Pasting is a high-power sputtering step in metal-mode depositing films of lower internal stress. This metal coating is expected to seal the highly stressed films from flaking. During the mirror coating process, an uninterrupted coating process is preferred to maximize the uniformity across the mirror and hence performing the “pasting process” in the middle of a dielectric coating is not the ideal solution.

In the current system, the following have been used to minimize flaking.

1. Reducing intrinsic stress by minimizing temperature variations
2. Effective rough/vent cycles
3. Effective shutter design
4. Optimized Shield design – texturing the components.

Intrinsic stress induced in the accumulated material within the mini chamber can be reduced by keeping the temperature of the parts low and stable. This can be accomplished by introducing an effective anode and eliminating the secondary electrons (as described in the previous section). It is also observed that most particles are generated during the rough and vent cycles (closer

to the viscous flow pressures) due to aggressive gas movements within the chamber. This was minimized by slowing down these processes especially closer to atmospheric pressures. Shutters are another source of particles especially when they are actuated during opening and closing operations. The speed of the shutter movement was optimized to minimize generation of particles without compromising the layer deposition control. In addition, a “catch-tray” design was introduced to collect any stray particles that are generated during the open/close actions.

Texturing the surface of the shields is known to provide improved adhesion and retention of the sputtered material deposited on them. Flame spraying and bead blasting are commonly used techniques to texture chamber components. Masks, shields and removable shutter areas within the mini chamber were all flame sprayed. Figure 4, shows images of a few flame-sprayed components.

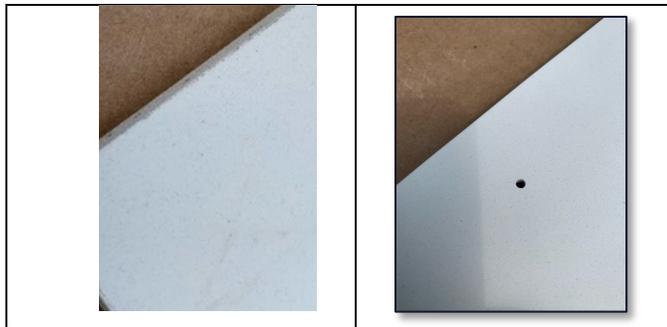


Figure 4 : Flame sprayed parts

Figure 5 represents the particles before and after flame-spraying the components of the cathode box. As can be observed, flame-spraying nearly eliminated the flaking of metals.

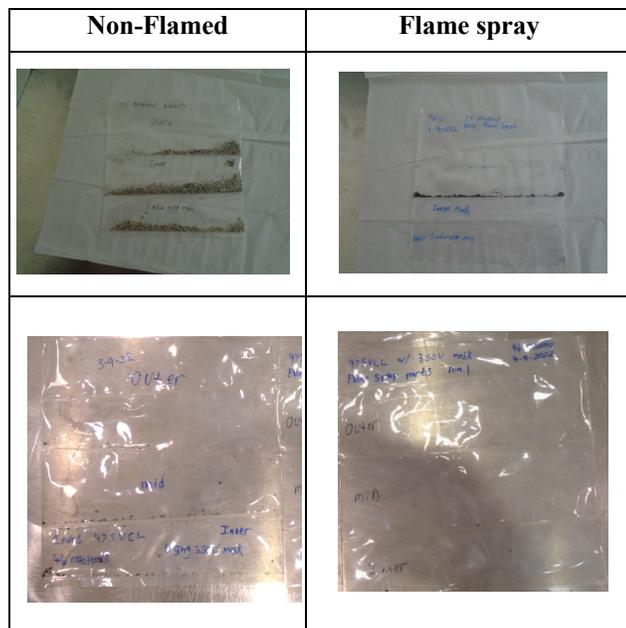


Figure 5: (A) Inside mini chamber (B) On the substrate

Process Development and results

Coating telescope mirrors is an expensive and time-consuming process. Therefore, a detailed and thorough process optimization was done on microscopic slides and optical grade substrates to obtain the required film properties. The witness samples were mounted radially from the center to edge on various simulated mirror configurations. The mirror setup was designed to follow the curvature, size, and shape of the actual mirrors (Figure 6).

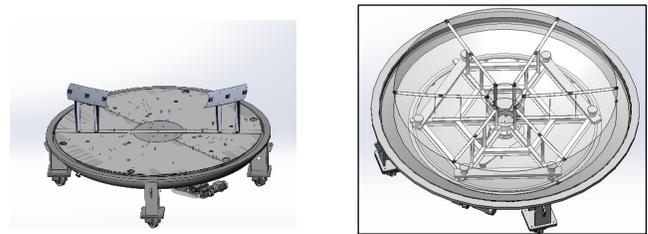


Figure 6: Simulated Mirror setup

Film thickness and optical performance was measured using reflectometer and spectrophotometer respectively. For process tuning of deposition rates and thickness, crystal sensors were positioned across the radii 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. The reflectance measurements for various reflectors are shown in Figure 7.

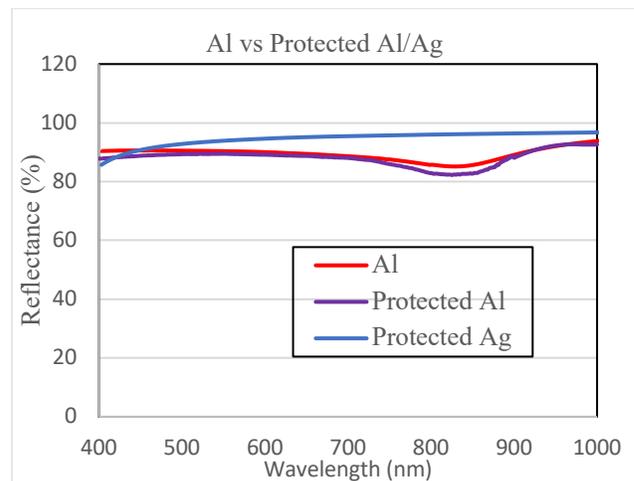


Figure 7: Optical Reflectance for various reflectors

The dielectric layer thickness can be optimized to meet the optical properties required for the wavelength of interest and to withstand aggressive environmental conditions. Figure 8 shows the optical properties protective Aluminum films with varying dielectric layer thicknesses.

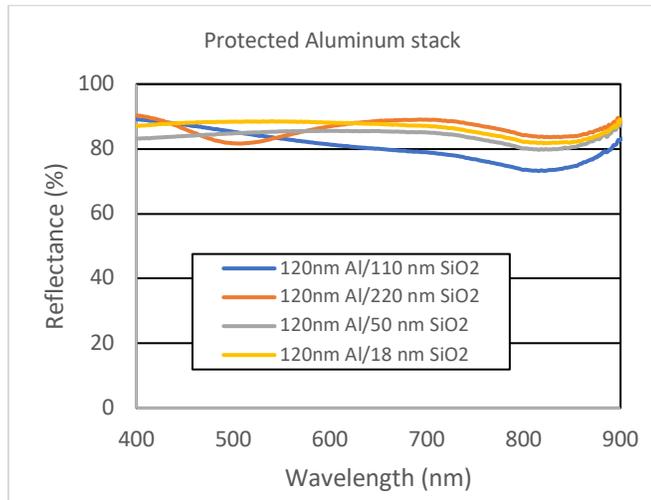


Figure 8: Optical Reflectance for protective Aluminum films with various dielectric thicknesses.

All the films were tested for extreme environmental conditions. The stress tests include:

- Salt mist
- Damp heat test
- Slow temperature Change
- CO2 clean test
- Cleaning test
- Adhesion
- Abrasion

Increased dielectric layer thickness (> 50nm) was required to successfully meet the aggressive abrasion tests. All film stacks successfully passed the rest of the environmental stress tests.

CONCLUSIONS

The system configuration of a telescope mirror coater was discussed in detail. A combination of active feedback control on process parameters, effective anode, and efficient hardware design play crucial role in overcoming the concerns related to thick dielectric coatings such as stability of the reactive sputtering process, reliability of the system components and particles. Protected reflector coatings optimized for optical performance and environmental durability were successfully deposited and the results were published.

ACKNOWLEDGEMENTS

The author would like to thank Carl Smith (Boeing), Thomas J. Todaro (Advanced process systems) for their contributions in this work. The author appreciates the valuable efforts from Dynavac team members.

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