Mirror coatings for large aperture UV optical infrared telescope optics

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ABSTRACT

Large space telescope concepts such as LUVOIR and HabEx aiming for observations from far UV to near IR require advanced coating technologies to enable efficient gathering of light with important spectral signatures including those in far UV region down to 90nm. Typical Aluminum mirrors protected with MgF_2 fall short of the requirements below 120nm. New and improved coatings are sought to protect aluminum from oxidizing readily in normal environment causing severe absorption and reduction of reflectance in the deep UV. Choice of materials and the process of applying coatings present challenges. Here we present the progress achieved to date with experimental investigations of coatings at JPL and at GSFC and discuss the path forward to achieve high reflectance in the spectral region from 90 to 300nm without degrading performance in the visible and NIR regions taking into account durability concerns when the mirrors are exposed to normal laboratory environment as well as high humidity conditions. Reflectivity uniformity required on these mirrors is also discussed.

Keywords: Large telescope optics, LUVOIR, HabEx, Aluminum mirror, far UV astrophysics, ALD, optical coating

1. INTRODUCTION

It has been recognized that in the mid to far ultraviolet wavelengths ($90 < \lambda < 300$ nm), it is possible to detect and measure important astrophysical processes, which can shed light into the physical conditions of many environments of interest in space. The astrophysics of a variety of Cosmic Origins science drivers requires access to ultraviolet emission diagnostics down to the Lyman edge at 912 Å. For example, in the local interstellar medium (LISM) all but two (Ca II H and K lines) of the key diagnostic of resonance lines are in the ultraviolet (Redfield[1] 2006). In addition to the fruitful science areas that ultraviolet spectroscopy has contributed since the early 1970s, France[2] *et al*. (2013) have emphasized the role of ultraviolet photons in the photo-dissociation and photochemistry of H_2O and CO_2 in terrestrial planet atmospheres, which can influence their atmospheric chemistry, and subsequently the habitability of Earth-like planets. However, only limited spectroscopic data are available for exoplanets and their host stars, especially in the case of M-type stars. Similarly, new areas of scientific interest are the detection and characterization of the hot gas between galaxies and the role of the intergalactic medium (IGM) in galaxy evolution (Shull[3], *et al*., 2012). The Hubble telescope throughput cuts off around 1150 Å. The Far Ultraviolet Spectroscopic Explorer (FUSE) is "no longer operational and as such the community has lost its window on a set of critical spectral diagnostics, such as for H2 and O VI, that are only available below 1150 Å." [McCandliss[4], *et al* (2010)].

The NASA Cosmic Origins Program Annual Technology Report (COR Technology Needs[5,6], Table 7, Item 8.1.3., page 43, Oct 2011) defined the need for the "Development of UV coatings with high reflectivity (>90-95%), high uniformity (<1-0.1%), and wide bandpasses (~100 nm to 300-1000 nm)". More recently, the Advanced Technology Large-Aperture Space Telescope (ATLAST) technology team assessed and stressed the technology development for maturing mirror coatings for the Far UV spectral range (Stahle[7], *et al*., 224th AAS Meeting, Boston, 2014 and Bolcar[8] *et al.*, SPIE conference on UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VII, 2015, paper 9602-8). A comprehensive summary of the Far UV science requirements (a Science Traceability Matrix (STM)) compiled

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by Paul Scowen[9], can be found at http://cor.gsfc.nasa.gov/RFI2012/rfi2012-responses.php. Important spectral lines in the FUV region are emphasized for general astrophysics observations. The NASA Astrophysics 30-year roadmap, Enduring Quests, Daring Visions, lists broadband coatings as one of the key technologies needed for LUVOIR to address a broad range of astrophysical questions "from cosmic birth to living Earth," combining general astrophysics and direct imaging and spectroscopy of exoplanets [Kouveliotou[10] 2014]. Thus high reflectivity coatings covering the 100-300 nm spectral range are considered important for studying intergalactic matter (IGM). "The COPAG is considering a future large UVOIR mission for general astrophysics that would also perform exoplanet imaging and characterization. Some technologies may be specifically required to make these two missions compatible, for example telescope coatings" [COPAG Technology Assessment[5] 2011, page 5]. Bolcar[11,12], *et al.*, assessed the technology requirements in "A Technology Gap Assessment for a Future Large-Aperture Ultraviolet-Optical-Infrared Space Telescope" [in the Journal of Astronomical Telescopes, Instruments, and Systems (JATIS) 2016; also see Proc. SPIE Vol. 9602 and Vol. 10398]. Similarly the Habitable Exoplanet Exploration Program (HabEx) aims to develop a large mission with a 4m aperture telescope. (Martin[13], *et al*., Proc. SPIE Vol. 10398, 2017, also Scowen[14] *et al*., and Stahl[15], *et al.*, in the same Proc. SPIE Vol. 10398, 2017).

2. BACKGROUND

A successful pathway to achieve the objectives, namely to develop durable mirror coatings that will provide high reflectance over the extended spectral band in the far ultraviolet (FUV) to near infrared (NIR), requires the best choice of materials and processes. Void-free thin films of absorption-free materials are required to protect and maintain high reflectivity and durability of aluminum mirrors in laboratory and pre-launch environments. Precisely controllable and scalable deposition process is also required to produce such coatings uniformly on large telescope mirrors.

The main objectives are thus, a) to explore materials and processes to produce protective coatings for Al mirrors to perform with high reflectivity over a wide spectral range from the far UV to NIR, and b) to demonstrate fabrication of durable mirror coatings with chosen processes on distributed coupons representing a meter class mirror. To begin with, we investigated the applicability of common dielectric materials and known processes and identified promising candidates (Bridou[16], *et al*., 2010, Keski-Kuha[17], *et al*., 1999, Yang[18], M., *et al*., 2005). MgF_2, LiF, AlF_3 stand out as primary promising materials for protective coatings while GdF_3, LaF_3 and LuF_2 are other potential materials to be considered. We produced coatings of some of these materials by conventional vacuum deposition process and measured their basic properties. (Balasubramanian[19,20], *et al*, 2014, 2015). Over the past year, we conducted several coating experiments with conventional physical vapor deposition (PVD) techniques as well as Atomic Layer Deposition (ALD) to produce thin MgF_2 and AlF_3 protective coatings. With the 1.2m coating chamber at Zecoat Corp., Torrance, CA, we produced a number of samples with chosen process conditions. Similarly, we produced several samples of newly developed ALD protective coatings on Al at JPL (Hennessy[21-26] *et al*., 2015, 2016, 2017). We employed a Perkin Elmer UV-VIS spectrophotometer at JPL and an ACTON FUV spectrophotometer at GSFC to measure the reflectance properties of these samples. A spectroscopic ellipsometer was also employed at JPL to characterize the films. Theoretical model fits of measured characteristics were analyzed. Key advances have been made on the ALD front with successful process development for MgF_2, AlF_3 and LiF coatings at moderate temperatures. Environmental impact on the stability of samples produced by PVD as well as ALD are detailed in the sections below.

Single layer coatings of applicable transparent protective materials by conventional PVD process

Single layer coatings of MgF_2, LiF, AlF_3, LaF_3, Na_3AlF_6 and GdF_3 were produced initially with conventional coating processes in a 1.2 m size chamber fitted with resistive sources, electron gun and ion gun besides heater lamps, LN traps, cryo pumps, residual gas analyzers and computer controls, at pressures in the range of $2x10^{-7}$ to $1x10^{-6}$ Torr and temperatures in the range of 20 to 200 °C. Figure 1 shows the coating chamber employed for this purpose. A sample transport with masking mechanism was installed in the chamber. This enables multiple coatings on different samples without breaking vacuum. An FUV optical monitoring system was also installed in the system to measure reflected signal from the growing film during

Figure 1. A 1.2 meter coating chamber fitted with process controllers, thickness monitor and gas analyzer. (courtesy: Zecoat Corp)

deposition and post deposition conditions such as total pressure, water vapor and oxygen content etc., for diagnostic purposes. MgF_2, LiF and AlF_3 are considered the most promising ones based on their UV transparency as evidenced by results from these initial experiments. The other materials, particularly the high index fluoride materials, could be employed in other multilayer devices such as filters and beam splitters. Several coatings were prepared on fused silica and silicon substrates. Spectral performance of these coatings were measured with state of the art spectrophotometers.

Protected Al mirror performance

Employing MgF_2, AlF_3 and LiF materials, single layer and bilayer protected Al mirror samples were produced earlier in 2013 with conventional physical vapor deposition (PVD) process in the chamber described above and reported earlier. The experimental data indicated a preference for AlF_3 as protective layer. Figure 2 shows the spectral reflectance performance of a bi-layer (LiF+AlF_3) protected Al mirror sample over the FUV to NIR spectrum measured over a period of 3 years after fabrication. Excellent stability is seen. The sample remained in the lab in a dry nitrogen flow box except during transportation and measurements each time involving a few days of exposure to normal environment with ~30 to 50% variable humidity. While UV to NIR (200 to 1000nm) reflectance measurements were done at JPL, FUV (50 to 200 nm) measurements with an ACTON or McPherson FUV spectrophotometer were done at Goddard Space Flight Center (GSFC). Optimization and enhancement of reflectance in the 100 to 200 nm range is a subject of further experimental investigation of process conditions and layer structures. In this context, research done at GSFC has been reported (Quijada[27-29] *et al*, 2012, 2104, 2017). ALD deposition of such coatings is now in progress at JPL (Hennessy[26] *et al*, 2017).

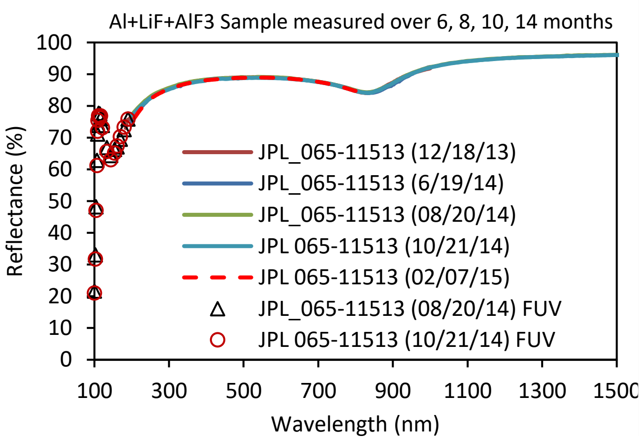

Figure 2 (A). Measured reflectance of a PVD bi-layer protected Al mirror sample 065 (AlF_3+LiF on Al) measured 6, 8, 10, and 14 months after fabrication showing excellent stability. Results over the FUV to NIR spectral range.

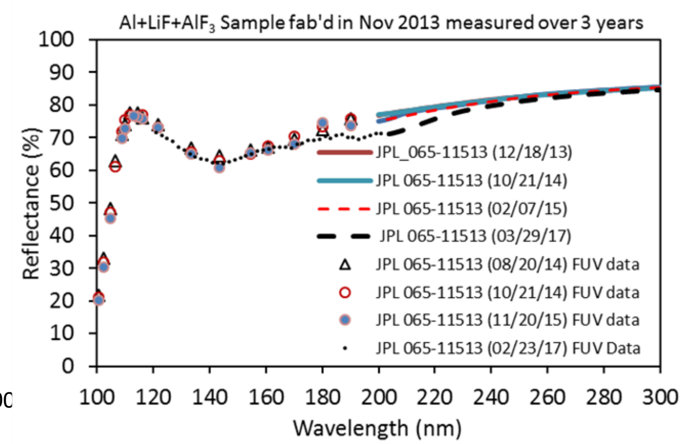

Figure 2 (B). Expanded view of the data in Fig 4(A) showing details in the FUV range. Measured over a period of 3 years since fabrication.

With further refinement of process details and controls in the conventional coating chamber, we prepared another set of samples of MgF_2- and AlF_3-protected mirrors with Al and LiF layers in 2015. The outer most layers were only about 4 to 5nm thick. FUV measurements of such tri-layer samples indicate a reflectance greater than 75% achievable at 110 nm and greater than 50% at 100 nm (Fig. 3). Further optimization of coating thicknesses and process parameters is necessary to further enhance the FUV reflectance. These samples Z11 and Z15 were measured over time to assess their stability as discussed later in section 5.

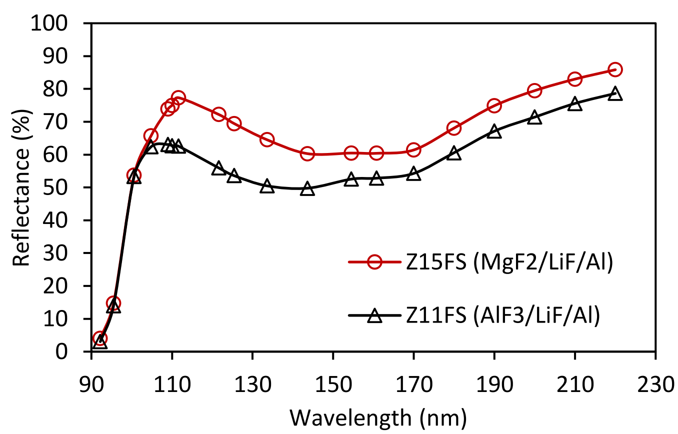

Figure 3. FUV reflectance of tri-layer mirror samples from conventional PVD coating

3. ATOMIC LAYER DEPOSITION (ALD)

ALD process is under development at JPL to produce MgF_2, LIF and AlF_3 protective coatings for high reflectivity mirrors with an Oxford OpAl showerhead-style ALD reactor shown in Fig. 4 and a Beneq ALD system shown in Fig. 5.

ALD films were deposited using bis(ethylcyclopentadienyl) magnesium ($Mg(EtCp)_2$) and trimethylaluminum (TMA) as the metal-containing precursors and anhydrous hydrogen fluoride (HF) as the fluorine-containing precursor in our Oxford reactor. Although metal fluorides are not common ALD materials, there have been several previous reports of their deposition often using metal fluorides such TaF_5 or TiF_4 as the fluorine-containing source. [Pilvi[30] 2007, Mantymaki[31] 2013] This tends to result in residual metal contamination which degrades the absorption properties in the far UV and results in a process which can only be performed at substrates temperatures greater than 250 °C. As a result of this high deposition temperature, the fluoride films deposited with this method tend to crystallize readily resulting in significant surface morphology which is undesirable for many optical applications. In contrast, the JPL-developed ALD process using HF results in fluoride materials with lower residual contamination that can also be deposited at low temperature resulting in smoother, denser films. Further AFM studies will more precisely investigate the surface roughness of these materials as a function of process conditions.

Figure 4. ALD coating system at JPL; gas feedthroughs and process controls enable AlF_3 and MgF_2 coatings development

As part of this effort, MgF_2 and AlF_3 were deposited at substrate temperatures ranging from 100 °C to 250 °C. Film thickness and refractive index were measured by spectroscopic ellipsometry and monitored as a function of process conditions such as process purge times and substrate temperature. Recent results on the same JPL ALD materials have been reported showing good optical performance at wavelengths down to 90 nm. [Moore[32] *et al.*, 2014, Hennessy[20-26] *et al.*, 2015, 2016, 2017].

Typical ALD conditions involve heating of the $Mg(EtCP)_2$ precursor which is then bubbled with Ar into the process chamber at exposure times of approximately 1 sec. TMA and HF are delivered by vapor draw at room temperature at shorter exposure times of 15-30 ms. The chamber is purged with Ar between each half-cycle exposure in the ALD process in order to ensure saturated, self-limiting deposition. We have demonstrated both MgF_2 and AlF_3 films with thickness uniformities better than 1% over six inches in diameter. Initial XPS measurements suggest that the films are approximately stoichiometric and further experiments will investigate how material composition changes as a function of process conditions. Deposition of LiF, a crucial material for FUV coatings, is also under development now with initial promising results. More details of the ALD developments at JPL can be found in Hennessy[26], *et al*, paper in Proc. SPIE 10401-41, 2017.

Figure 5. Beneq ALD deposition system at JPL

A key goal in the development of ALD process is to optimize the process acceptably low temperature, i.e., to be below 100 °C, in order to enable large mirror coatings at high vacuum. Our recent experiments indicate that this is achievable in the near term for the relevant fluoride materials.

Reflectance degradation of Al due to oxidation

To assess the nature and progression of oxide formation on fresh Al coating, we conducted a series of control experiments with Al coatings of different thicknesses deposited at different rates at a high vacuum of ~2×10^{-9} Torr in an UHV chamber at JPL. Figure 6 shows the measured (symbols) and modelled (lines) performance of an unprotected Al mirror in the wavelength range from 190 nm to 290 nm over a period of about 1500 minutes after deposition. A nm of oxide formation is estimated to be sufficient to degrade the reflectance as shown. Figure 7 shows the measured reflectance in the far UV of an unprotected Al mirror and its model fit with an oxide formation of different thicknesses. These measurements and simulations show that an oxide layer of < 2nm thickness affects the FUV reflectance dramatically in a very short time.

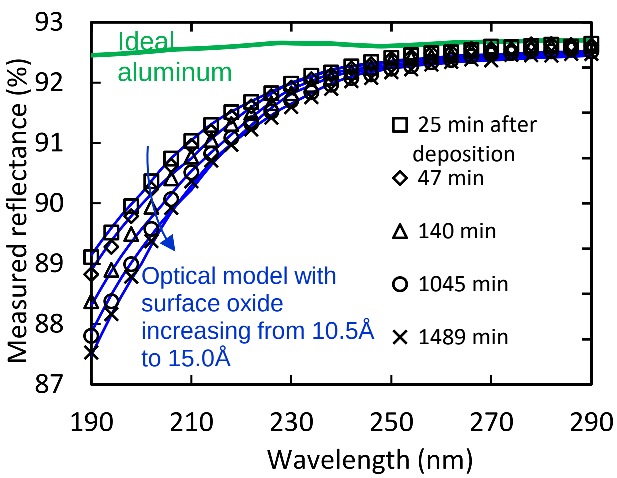

Figure 6. Oxidation induced reflectance reduction in the near UV of an Al mirror sample; model fits (lines) match (measured data symbols) a progressive increase of oxide formation.

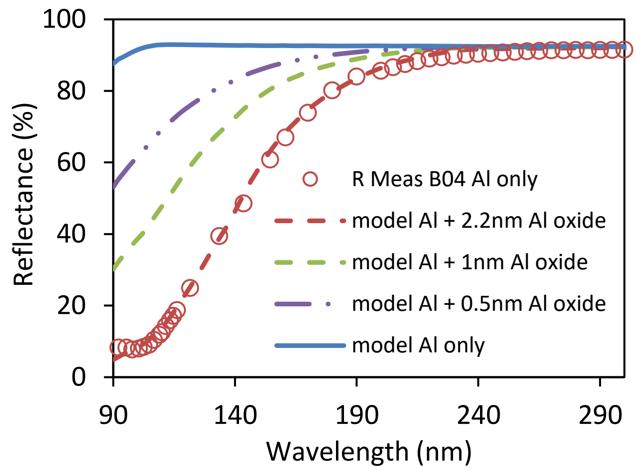

Figure 7. Unprotected Al reflectance (ideal) and modelled with a thin oxide layer matched measured characteristics in FUV spectral range.

Deposition Rate

Rate of deposition of the Al layer is a critical parameter that affects the reflectance as well as its stability over time. Samples were fabricated at different rates in high vacuum with a base pressure of ~2×10^{-9} Torr. Initial measurements clearly indicated (Fig. 8) that a rate much higher than 20Å/sec would be favorable for obtaining better reflectance in the FUV due to denser microstructure and lower oxidation in the bulk of the Al layer compared to lower rate samples.

Surface microstructure and roughness

The microstructure and surface roughness of the Al samples deposited in UHV conditions at different rates were examined. Figure 9 and Table 1 below show the AFM images of samples deposited at 1A/s and 17A/s clearly indicating smoothness and higher reflectance achievable with higher deposition rates.

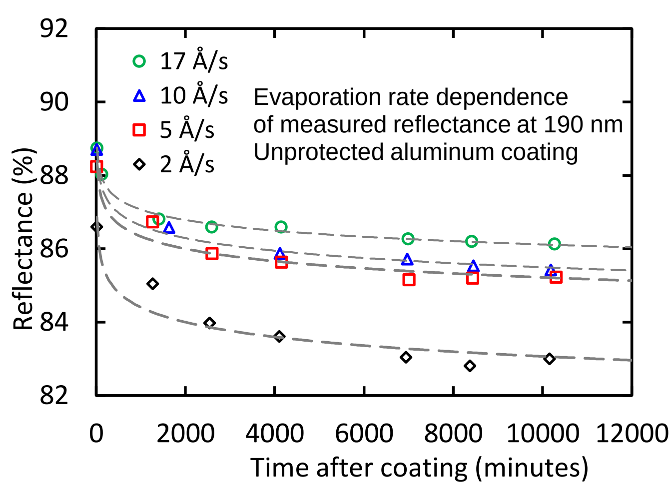

Figure 8. Measured reflectance at 190nm wavelength vs time after coating of unprotected Al samples fabricated with different evaporation rates

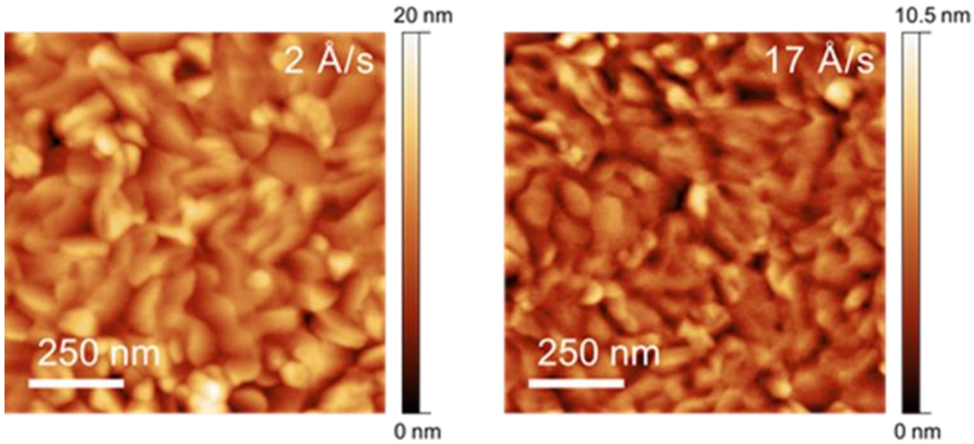

Figure 9. AFM images at a length scale of 1x1 µm of UHV electron beam evaporated Al films (60 nm thickness) at deposition rates of 2 Å/s (left) and 17 Å/s (right).

Evaporation Rate (Å/s)	*Micro-roughness 1x1 µm (nm rms)*	*XPS [O 1s] / [Al 2p] ratio*	*Reflectance after 1 week at 190 nm (%)*
2	2.05 (±0.14)	1.3 (±0.2)	83.0
5	1.45 (±0.09)	1.3 (±0.2)	85.2
10	1.30 (±0.08)	1.3 (±0.2)	85.5
17	1.18 (±0.03)	1.1 (±0.2)	86.1

Table 1. The influence of evaporation rate on the UV reflectance at 190 nm for Al thin films deposited by electron beam evaporation at a base pressure of ~2×10^{-9} Torr. The mean rms roughness and standard deviation averaged over five scans for each of the four samples analyzed in Fig. 8.

A phenomenological refractive index model to estimate the optical properties of the surface oxide was developed to assess the performance impact of a brief air exposure prior to deposition of a protective layer. Details of this model and analysis can be found in Hennessy[23,24] *et al.*, 2016. The n and k derived from such model for the oxide and AlF_3 film and are plotted in figure 10. (adopted from Ref :24).

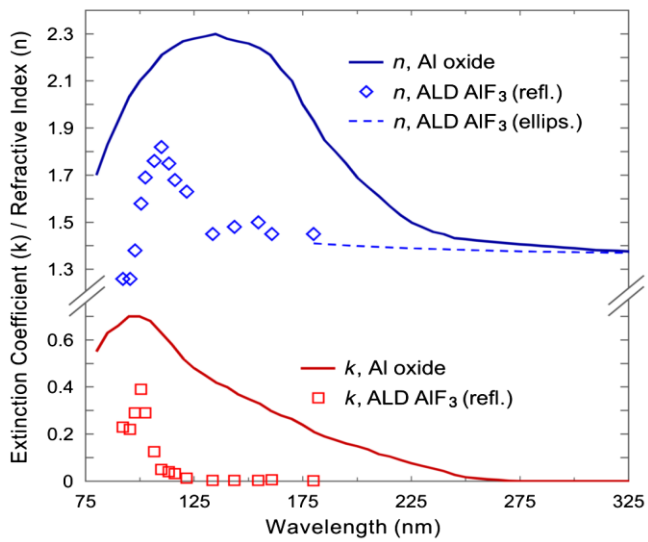

Figure 10. Phenomenological refractive index model for the interfacial native oxide on evaporated Al thin films, and the refractive index model for ALD AlF_3 derived from isoreflectance analysis in the FUV.

4. RESULTS WITH CONVENTIONAL PVD COATINGS AND ALD COATINGS

A series of AlF_3-coated Al mirror samples were prepared with different thicknesses of the protective fluoride coated with the ALD process. The UV reflectance of five of these samples with different thicknesses of the protective layer was measured over several days and reported earlier (Balasubramanian[20] *et al.*, 2015). It was inferred that a very thin layer (~ 3 to 5nm thick) of AlF_3 could protect the LiF coated Al mirror. More samples protected with AlF_3 films of different thicknesses are shown in figure 11. The absorption edge of the sample moves to the shorter wavelength end with thinner layer as would be expected. Figure 11 also shows the measured FUV reflectance of the ALD AlF_3

protected Al mirrors in comparison with a commercial PVD MgF_2 protected Al mirror. Model fits of the measurements indicate a thinner oxide formation in the Al layer when thicker protective coating is applied.

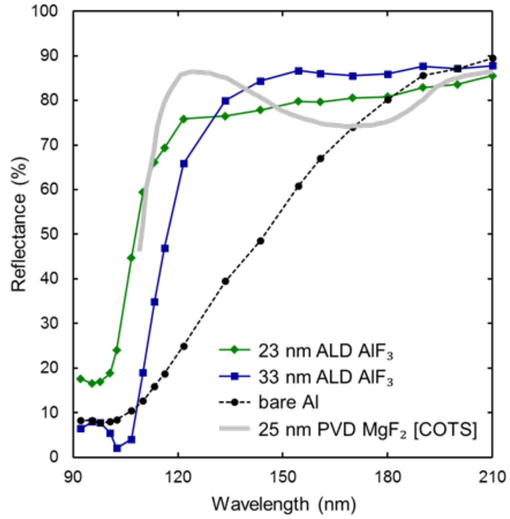

Figure 11. Measured FUV reflectance (symbols) and the corresponding calculated optical model (dashed lines) of ALD AlF_3 protective coatings of various thickness deposited on e-beam evaporated Al thin films, compared to an unprotected Al coating and a typical high-performance PVD MgF_2 protected mirror

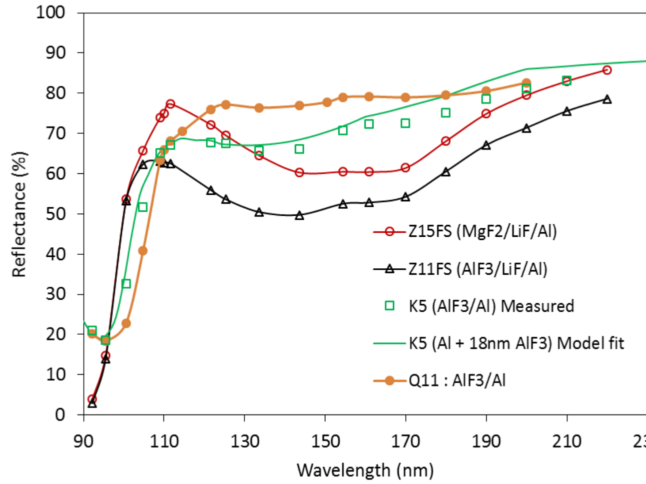

Figure 12. FUV reflectance of tri-layer mirror samples produced by conventional thermal evaporation (samples Z11 and Z15); bi-layer mirror samples produced by e-beam of Al and ALD of AlF_3 (samples K5 and Q11)

Figure 12 compares the FUV performance of four different coatings. Samples Z11 and Z15 were produced by conventional thermal evaporation techniques in the same chamber as of sample 065 in figure 2 but with different process conditions of sources and rates. Samples K5 and Q11 were produced with a combination of e-beam evaporation of Al in a UHV chamber and ALD coating of AlF_3 in an Oxford ALD chamber. The sample had to be transferred from the UHV chamber to the ALD chamber during which time it was exposed to ambient conditions. Such exposure for a few minutes causes oxide formation on Al surface and reduces its reflectance inevitably. Yet the reflectance is > 50% at 100nm and about 70% at 110nm as seen in these measurements. These experiments further enforce the need for more experiments and process optimization to reach >80% reflectance at 100nm as predictable by models.

Environmental Tests

The samples Z11 and Z15 (refer to figures 3 and 12) produced by conventional PVD processes early in 2015 were measured repeatedly over the past 2 years at GSFC. The main difference between these samples is that the outer most protective layer is either MgF_2 or AlF_3 with nearly same physical thicknesses around 4 to 5 nm. The measurements plotted in figure 13 show that the MgF_2 protected sample is more stable over the years compared to the AlF_3 protected sample. However, as the measurements indicate stabilization after the initial drop, particularly of sample Z11, we continue to monitor the performance of these samples.

We also prepared a few Al mirror samples with ALD AlF_3 protective layers for environmental tests. Preliminary test of one of the samples subjected to 24 hours in 96% relative humidity at 50°C shows a drop in reflectance in the near UV as seen in figure 14. This silicon substrate sample P04 was coated with Al by conventional e-beam technique and over coated with a thin ~3nm layer of AlF_3 by ALD. While this sample made in Sep 2015 showed no noticeable change in reflectance after ~1 year of storage in the laboratory, it suffered when subjected to high humidity at elevated temperature as seen above. The drop in reflectance at 200nm observed in this preliminary test suggests that further tests are needed, besides optimization of the process conditions and layer thickness. As discussed earlier in section 2, a sample of AlF_3 + LiF protected Al coated by conventional PVD technique has shown little degradation over 3 years (Figure 2) in normal laboratory conditions. Further work is therefore needed in this area to arrive at firm conclusions and to improve performance and stability.

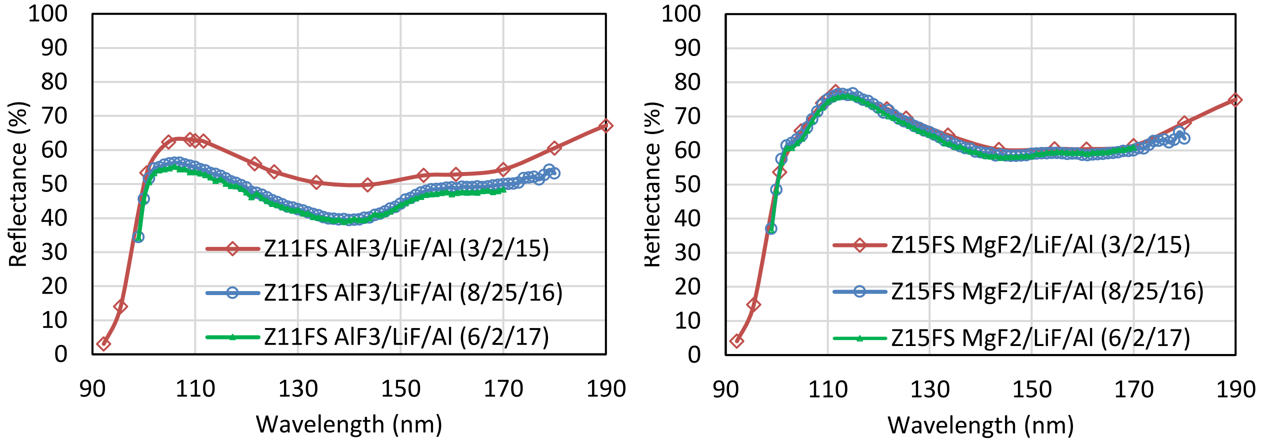

Figure 13. Environmental stability of mirror samples Z11 (left) and Z15 (right) over two years of normal storage in lab at 30 to 50% RH and 25°C conditions except during sample transport and measurements.

Atomic Layer Etching (ALE) to remove surface oxide

Early experiments with ALD AlF_3 protective coatings gave promising results on performance and stability of Al mirrors in laboratory environment as shown in our earlier reports (Hennessy[21,22] *et al.*). Recent experiments with ALD coating of a protective fluoride layer after atomic layer etching (ALE) of the surface oxide on Al improves the reflectivity significantly[23-25]. Both MgF_2 and AlF_3 protective overcoats were deposited by ALD after ALE removal of oxide on Al. Measurements of reflectivity of these ALE + ALD coating samples under controlled conditions and high humidity exposures are shown in figures in 15A and 15B.

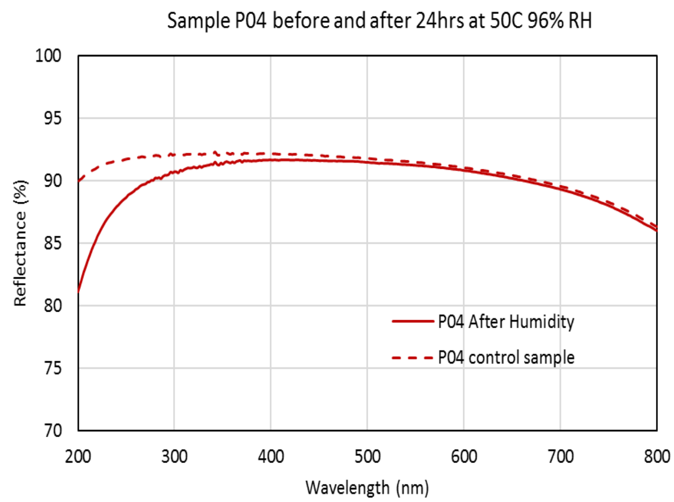

Figure 14. Measured reflectance of an Al +ALD AlF_3 coated Si wafer sample subjected to 24 hours in 96% relative humidity at 50°C in an oven with K_2SO_4 salt to produce and maintain the RH level.

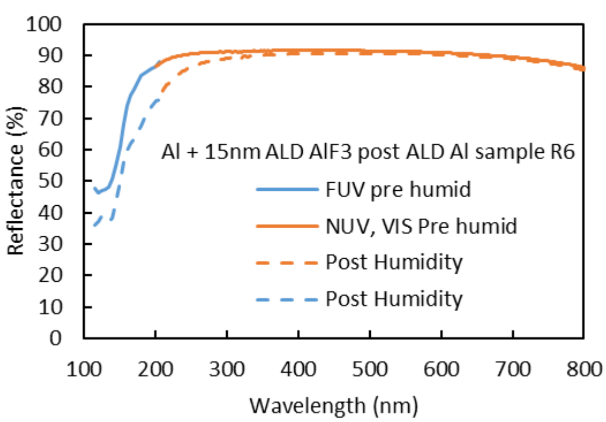

Figure 15A. (Left) Measured reflectivity (before and after 24 hrs at 80% Relative Humidity at 50 °C) of a sample with ~15nm AlF_3 ALD layer on Al after ALE procedure to remove surface oxide.

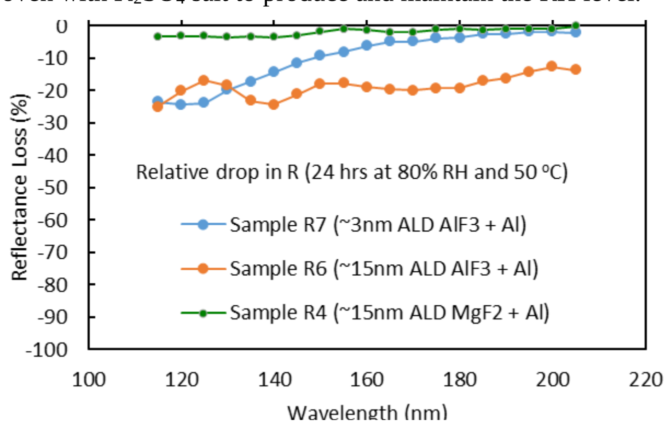

Figure 15B. (Right). Relative change in reflectivity of similar samples of different thicknesses of AlF_3 and MgF_2 on Al after ALE process indicating the superior stability of MgF_2 protected sample.

The observed drop of about 10 to 20% with AlF_3 layers relative to unexposed control sample suggests the need for further optimization. Starting reflectance of these samples at 120 nm were 51% (sample R7), 46% (R6), and 61% (R4). Without the ALE process, the drop in reflectivity would have been much worse as we observed in our earlier experiments. While this experiment shows improved reflectivity of such a coating, it reveals that the AlF_3 layer has some vulnerability to moisture attack and hence needs further improvement and protection. Optimization of thickness and process conditions are now necessary. The ALE procedure greatly reduces the extreme care needed with load lock transport of samples for ALD coating after Al evaporation in a conventional chamber.

Polarization, uniformity, and contamination considerations for large telescope performance

In addition to the FUV to NIR spectral range to be covered, large aperture high performance telescopes have to consider a few other metrics, such as polarization, uniformity, and contamination.

Polarization properties of the system depend critically on the f/# of the primary mirror as also the angles of incidence encountered at other mirrors. System design aspects have to be optimized to control the polarization impact. HabEx plans to employ an f/2.5 primary to mitigate the polarization effect (Martin[13], *et al.*, 2017). Fine tuning the coating design can also optimize the polarization performance (Balasubramanian[33] *et al.* 2011) to some extent in the specific spectral range most relevant to coronagraphy.

Coating uniformity is mainly a result of the coating process controls relevant to the specific chamber geometry. Theoretical analysis suggests that a non uniformity of <0.5% over the aperture would be needed for adequate coronagraph contrast performance at the 10^{-10} level; the specific details of the requirement depends on the spatial frequency of the variation, the coronagraph observation region (inner and outer working angles), spectral bandwidth, the efficiency of the deformable mirrors to correct amplitude and phase errors, etc., However the coating uniformity is a basic requirement that depends on the coating process. For example, the 1.4m size Kepler telescope primary mirror with 0.95m entrance aperture had a coating of protected silver (Sheikh[34] *et al.*, 2008) and showed a thickness non uniformity of about 30nm p-v with about 2.5% reflectivity variation. Similarly, the JWST gold mirrors showed <10nm pv thickness nonuniformity with <0.5% reflectance non uniformity in the IR among its 18 hexagonal segments (Lightsey[35] *et al.*, 2012).

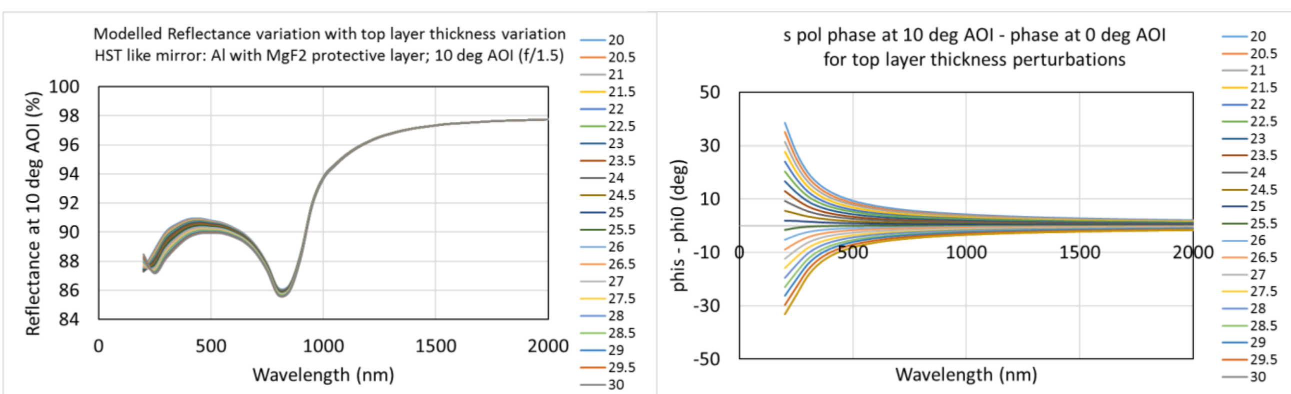

Figure 16 A (Left). Model analysis of reflectivity uniformity of a HST-like mirror (nominally 25nm of MgF_2 over Al); the top protective layer is varied by +/-5nm which results in a reflectance variation of +/-0.75% at 400nm. Figure 16 B (Right): Model analysis of reflected phase variation when the top layer thickness is varied by +/-5nm. Max phase variation is ~ +/- 35 deg (~0.2wv p-v) in the UV and +/-8.5 deg at 500nm; Δphase will be <+/-3.5 deg (0.02wv p-v) at 500nm if Δthickness is +/-2nm.

On ground based large systems such as the SUBARU telescope with 8.3m monolithic mirror coated with Al, the coating thickness variation was reported as ~20nm pv (Hayashi[36] *et al.*, 1998, Kurakami[37] *et al.*, 2003). More recent results with current processes may present better uniformity. Therefore for the large space borne mirrors on HabEx and LUVOIR, practical constraints in the coating chamber and processes may affect the uniformity thus prompting a careful study. A simple model analysis of reflectivity and phase variation across a typical HST-like mirror coating (Al $+MgF_2$) with notional thickness variation on the top most layer alone is shown in figures 16 A and B. It is observed that tight process control to the level of +/-2nm of the protective layer of MgF_2 will be needed to control the reflectance and phase variation to the required levels. Figure 16 A shows the variation of reflectivity if the outer most layer thickness is varied by +/-5nm; similarly figure 16 B shows the reflected phase variation for +/-5 nm variation. Only one polarization is considered in this analysis. If the process can be controlled to +/-2nm level, the effective performance may be within the limits of the DMs with adequate stroke range.

Particulate contamination of the mirror surface during integration and testing can impact the reflectivity significantly. For example, the Hubble Space Telescope (HST) mirror was assessed to have had a 3% obscuration due to contamination before launch and another 2% was expected during launch (Ref: HST OTA Handbook[38] 1990). Surface contamination can also cause unacceptable level of scattering for the coronagraph performance (Ref: Balasubramanian[39] *et al*., 2009). Hence tighter engineering protocols would be required to preserve the mirror cleanliness level before launch.

Uniformity tests with conventional evaporation

To test the uniformity of the Al coating on a meter class optic with conventional PVD techniques, a preliminary study was conducted with a number of small coupons placed along the diameter of the coating chamber at Zecoat Corp fitted with a moving e-gun source, instead of fixed filament sources distributed around the chamber as is typically done for ground based astronomical mirrors. The results of this one preliminary test are plotted in Fig. 17. The process was not optimized for the UV range and hence the results show a larger variation of reflectance in UV than in the visible range. However, this is a preliminary study and is a subject for further optimization of the process to achieve better than 0.5% uniformity across a 1 m diameter and larger optic. In contrast, the ALD process is inherently uniform as it is not based on a line of sight deposition. Thermal conditions and gas flow over the area of the optic will determine the uniformity achievable with ALD. Thus significant research and engineering effort is considered necessary to accomplish high uniformity of coating reflectivity and phase across larger mirrors envisioned with LUVOIR and HabEx mission concepts.

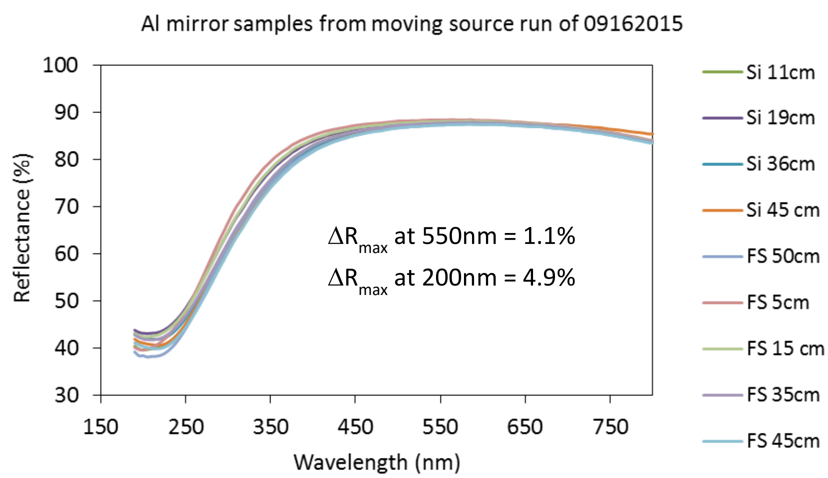

Figure 17. Uniformity tests: Coating experiment done with a moving source in a 1.2m chamber at Zecoat Corp. Legends indicate location of the samples from the center of the substrate holder geometry. While this serves as an example of one experimental run, further optimization of process conditions and geometry is feasible to achieve better results, particularly in the UV.

Path Forward

On the ALD technology, we now plan to focus on optimizing the ALD process parameters further and prepare samples of protected aluminum mirrors for reflectivity measurements. Lower temperature processes with faster cycle times are being developed in our ALD system now. Our models predict that very thin protective layers deposited by ALD process can accomplish higher reflectance in the FUV as shown in Fig. 18. Newly developed ALE process shows promise to remove the oxide on the Al surface to apply a protective layer. Figure 19 shows the recently fabricated Al mirror samples with and without the ALE process prior to the application of ALD AlF_3 protective layer. Details of these experiments and models can be found in Hennessy[24-26] *et al* (2016, 2017). Further development work is in progress with ALE + ALD process at

JPL. High rate deposition of Al followed by a thin protective layer with ALE + ALD process is likely to provide the required FUV reflectance and adequate protection. Similarly, conventional deposition techniques also need further investigation particularly with regard to improving reflectivity and uniformity over large area mirrors. A PVD process with very high rate deposition of Al followed by protective layers coated at the optimum temperature and pressure may reach the required performance level. Uniformity of reflectivity and phase has to be studied with both techniques particularly for large monolithic mirrors to be operated in space.

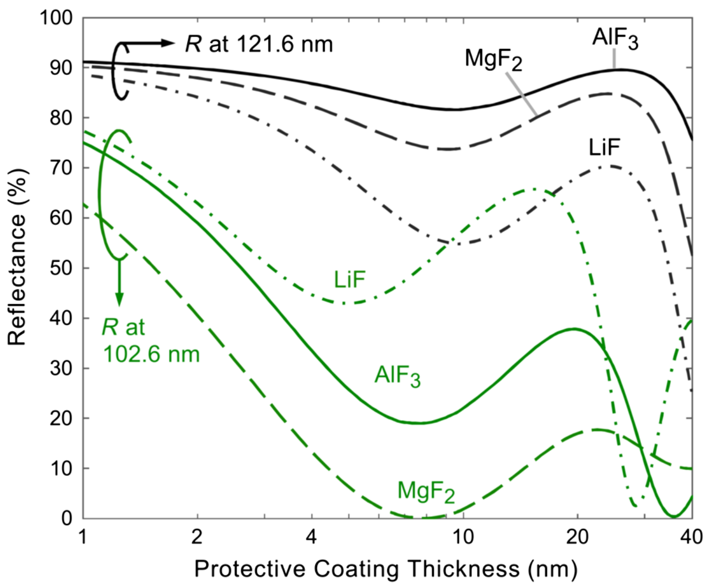

Figure 18. The calculated reflectance at 121.6 and 102.6 nm as a function of coating thickness for films of MgF_2, AlF_3, and LiF on ideal Al.

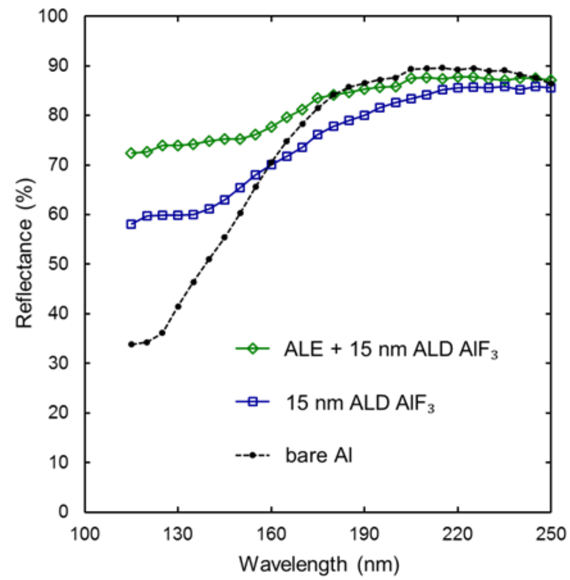

Figure 19. Measured FUV reflectance of Al samples with ALD AlF_3 protective layer with and without ALE process on the Al surface showing the improvement of reflectivity due to ALE.

5. SUMMARY

Large space telescope concepts for future missions such as LUVOIR and HabEx envision efficient gathering of light from far ultraviolet to near infrared with stringent requirements on throughput, uniformity, polarization and durability to enable coronagraphy of exoplanets as well as general astrophysics of the cosmos. Conventional vacuum deposition of Aluminum mirrors with AlF_3 and LiF as protective layers have shown stability of performance for over three years. Measured reflectance of these samples are in the range of 55 to 80% in the 100 to 120 nm FUV range while further improvements can be made with optimum layer thicknesses and process conditions. Deposition rate, temperature and vacuum level have significant effect on the reflectance as well as performance stability. ALD coating processes have also been developed at JPL for MgF_2, LiF and AlF_3 protective coatings. Protected Al mirrors with ALD fluoride layers have been fabricated successfully and modeled to guide further development.

- High TRL HST-like MgF_2 protected Al mirrors have flight heritage with proven long term performance in the spectral range >115nm.
- Reflectance performance in the 90 to 120nm range requires the use of LiF and AlF_3 layers to protect Aluminum from oxidation, though they show less stability compared to MgF_2.
- Protected Aluminum mirrors with PVD techniques have been produced with ~75% reflectance at 110nm with long term stability; these mirrors currently show ~55% reflectance at 100nm.
- Optimized protective layer of AlF_3 or MgF_2 on LiF deposited by ALD is likely to provide better FUV performance and stability; ALE + ALD process has shown great promise with >70% reflectance at 115nm and requires continued process development.
- Reflectance and phase uniformity necessary on large (>4m dia) monolithic mirrors need systematic study to raise the TRL level.

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