Mirror Coatings for large aperture UV to IR Telescopes

Bala K. Balasubramanian
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Mirror Tech Days 2016
2 Nov 2016
Greenbelt, MD 20770

Requirements and Challenges

- UV Optical IR telescope optics covering FUV to NIR
- High Reflectance including the far UV down to 90nm
- Large area, meter class optics
- High Uniformity
- Low Polarization
- Stability in the environment, robust protection
Reflectance of 200nm thick film on glass for four metals
Theoretical calculations based on optical constants from Palik

Aluminum is the obvious choice
Technical Challenges

Performance impact due to:

1. Chemical (contamination, oxidation, stoichiometry)
   Absorption
   Instability/durability

2. Microstructural
   Scattering
   Water vapor adsorption

3. Uniformity over large area

4. Polarization sensitivity
Unprotected Aluminum Mirror

Al mirrors samples

Unprotected Al

Al mirror sample

Unprotected Al with ~ 2 nm of oxide

% R

80

90

95

100

250 350 450

Wavelength (nm)

50

60

70

R (%)

100

90

80

70

60

50

0

10

20

30

40

50

60

70

80

90

100

100 150 200 250 300

Wavelength (nm)

R meas (%)  

R Calc (%)
On the Vacuum-Ultraviolet Reflectance of Evaporated Aluminum before and during Oxidation*
R. P. MADDEN, L. R. CANFIELD, AND G. HASS; JOSA Vol:53 No:5, May 1963
Unprotected Aluminum

Oxidation induced reflectance reduction in the near UV of an Al mirror sample; Models predictions match a progressive increase of oxide formation.

- Reduction of aluminum reflectance following air exposure has power law dependence on time
  - Power law exponent also has at least exponential dependence on wavelength
### Properties of Typical Deposited Thin Films for UV Optical Applications

<table>
<thead>
<tr>
<th>Material</th>
<th>Band Energy (eV)</th>
<th>~λ Cut Off (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lithium fluoride (LiF)</td>
<td>12 – 13</td>
<td>95</td>
</tr>
<tr>
<td>aluminum fluoride (AlF₃)</td>
<td>11 – 12</td>
<td>105</td>
</tr>
<tr>
<td>magnesium fluoride (MgF₂)</td>
<td>10 – 11</td>
<td>115</td>
</tr>
<tr>
<td>calcium fluoride (CaF₂)</td>
<td>9 – 10</td>
<td>125</td>
</tr>
<tr>
<td>lanthanum fluoride (LaF₃)</td>
<td>8 – 9</td>
<td>140</td>
</tr>
<tr>
<td>silicon oxide (SiO₂)</td>
<td>7 – 8</td>
<td>160</td>
</tr>
<tr>
<td>aluminum oxide (Al₂O₃)</td>
<td>6 – 7</td>
<td>190</td>
</tr>
</tbody>
</table>

- Aluminum has the highest reflectance in the ultraviolet, but reflectance below 200 nm is strongly suppressed by the presence of any surface oxide.
- Protective coatings can be applied to pristine Al surfaces to prevent oxidation and even enhance reflectivity due to interference effects.
- Currently developing and optimizing ALD processes at JPL for the three best candidate protective materials.
Background

• Standard coatings fall well below the natural reflectance of aluminum
  – A thin, dense, absorption free protective coating could greatly improve performance from 90-120 nm
• FUV has a significant number of spectral lines that are of great interest to astronomers
  – Stellar and galaxy evolution; protoplanetary disks and exoplanet atmospheres

A Protected Aluminum Mirror

Conventional Deposition

![Graph showing reflectance vs. wavelength for a protected aluminum mirror with JPL0065 composition (Al+LiF+AlF3 on Si Substrate), dated 10/21/14.](image-url)
Al+LiF+AlF$_3$ mirror aging performance

Measured reflectance of a bi-layer protected Al mirror sample measured 6, 8, 10 and 14 months after fabrication showing excellent stability. FUV to NIR spectral range.

Conventional Thermal Evaporation
Al+LiF+AlF₃ mirror aging performance

Measured reflectance of a tri-layer Al mirror sample measured 6, 8, 10, 14 and 23 months after fabrication showing excellent stability. Expanded view of the FUV spectral range.
Stability of Al mirror (sample K series) coated with thin AlF$_3$ layer by ALD

- ALD AlF$_3$ coatings have a measured long-term stability, and can also extend the short wavelength cutoff when compared to traditional methods
- Layers as thin as 3 nm have been demonstrated to be effective in suppressing the oxidation of aluminum
Even in UHV conditions (base pressure ~ 2 x 10^{-9} Torr), the reflectivity dependence on evaporation rate is significant
  – Impact on the saturated value of reflectance as well as the rate of degradation
FUV performance of ALD AlF$_3$/Al mirror samples

Model fits (dotted lines) of measured (symbols) FUV reflectance of unprotected (sample K1) and AlF$_3$ protected samples (K2 to K5).
**Al+LiF+AlF$_3$ mirror, Al+AlF$_3$(ALD) mirror**

- Conventional Thermal Evaporation (Z11, Z15)
- ALD of AlF$_3$ on e-beam Al (K5 and Q11)

### FUV reflectance of
- tri-layer mirror samples produced by conventional thermal evaporation
- bi-layer mirror samples produced by e-beam and ALD
- Optimization of layer thicknesses necessary to improve performance

**Wavelength (nm)**

- Ly-a 121.6nm
- Ly-b 102.6nm
- Ly Limit 91.2nm
- Balmer-g 108.5nm
Protected Al mirrors from JPL and GSFC produced with different processes

- Al + MgF2 (GSFC)
- Al + LiF (GSFC)
- JPL065-11513 Al + LiF + AlF3
- JPL Z15FS (MgF2/LiF/Al)
- Al2O3 (3A) + ALD AlF3 (3nm) + Al
- Al2O3 (0A) + ALD AlF3 (2nm) + Al

GSFC Data Courtesy: Manuel Quijada
Measured FUV reflectance (symbols) and the corresponding calculated optical model (dashed lines) of ALD AlF₃ protective coatings of various thickness deposited on evaporated Al thin films.

Throughput after 3 reflections: with 60% R from each optic at 100nm, throughput will be $0.6^3 = 0.22$

J. Hennessy, et al., JATIS 2(4), 041206 (2016)

The calculated reflectance at 121.6 and 102.6 nm as a function of coating thickness for films of MgF₂, AlF₃, and LiF on ideal Al.
Summary

• Protected Aluminum mirrors with \(\sim 75\%\) reflectance at 110nm with long term stability have been produced
• These mirrors currently show \(\sim 55\%\) reflectance at 100nm
• Protective fluoride layers coated with Atomic Layer Deposition indicate potentially better performance (>60% at 100nm) and stability

• References
Acknowledgements

John Hennessy, Shouleh Nikzad, Nasrat Raouf, Stuart Shaklan, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Paul Scowen, Arizona State University, Tempe, AZ 85287

Manuel Quijada, Javier Del Hoyo, NASA – GSFC (FUV Reflectance)

David Sheikh, and Josh Saadia, Zecoat Corporation, Torrance, CA

The work is performed at Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA Cosmic Origins Program

Thank You
Backups
## Significant FUV Spectral Lines

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Species</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>68.1, 69.4</td>
<td>Na IX</td>
<td>Coronal Gas ($&gt; 10^6$ K) Diagnostic (density, ionization state, etc.)</td>
</tr>
<tr>
<td>77.0</td>
<td>Ne VIII</td>
<td>Warm-Hot Gas ($5 \times 10^5$ - $10^6$ K) Diagnostic (density, ionization state, etc.)</td>
</tr>
<tr>
<td>91.2</td>
<td>H, Lyman Limit</td>
<td>Ionization Energy of Atomic Hydrogen</td>
</tr>
<tr>
<td>97.7</td>
<td>C III</td>
<td>Gas Electron Density Diagnostic</td>
</tr>
<tr>
<td>99.1, 175.0</td>
<td>N III</td>
<td>Gas Temperature Diagnostic</td>
</tr>
<tr>
<td>102.6</td>
<td>H, Ly-β</td>
<td>Lyman Series H Recombination Line</td>
</tr>
<tr>
<td>103.2, 103.8</td>
<td>O VI</td>
<td>Recombination Line Doublet</td>
</tr>
<tr>
<td>108.5, 164.0</td>
<td>He II</td>
<td>Balmer-γ line for He</td>
</tr>
<tr>
<td>117.5</td>
<td>C III</td>
<td>Gas Electron Density Diagnostic</td>
</tr>
<tr>
<td>120.6</td>
<td>Si III</td>
<td>Optically thin emission line of Silicon</td>
</tr>
<tr>
<td>121.6</td>
<td>H, Ly-α</td>
<td>Lyman Series H Recombination Line</td>
</tr>
<tr>
<td>123.8, 124.3</td>
<td>N V</td>
<td>Gas Emission Diagnostic</td>
</tr>
<tr>
<td>130.4</td>
<td>O I</td>
<td>Geocoronal Triplet Emission Line</td>
</tr>
<tr>
<td>133.5</td>
<td>C II</td>
<td>Absorption Line for ionized Carbon</td>
</tr>
<tr>
<td>139.4, 140.3</td>
<td>Si IV</td>
<td>Emission Line of Silicon</td>
</tr>
<tr>
<td>140.7</td>
<td>O IV]</td>
<td>Gas Density sensitive doublet</td>
</tr>
<tr>
<td>148.8</td>
<td>N IV]</td>
<td>Gas Diagnostic Line – sensitive in particular to electron collision strengths</td>
</tr>
<tr>
<td>154.8, 155.1</td>
<td>C IV</td>
<td>Gas density-sensitive doublet</td>
</tr>
</tbody>
</table>
Deposition Chambers

1.2m thermal / ebeam evaporation chamber (Zecoat Corp) with a moving source

Beneq ALD reactor (JPL)

Oxford ALD reactor (JPL)
Commercial solutions for large area atomic layer deposition include (left) systems for high performance optical coatings [MLD Technologies, mldtech.com], (middle) deposition on meter-class substrates for photovoltaic applications [Putkonen 2009], and (right) large area roll-to-roll ALD reactor [Beneq, beneq.com]
VUV enhanced Al mirrors

Measured reflectivity of Al mirrors with various protective layers

Al+LiF Mirror FUV Performance (GSFC)

Recipe: Al (43nm, ambient)+LiF(8nm, ambient)+LiF(16.4nm, 250°C)

\[ R_{ave}(100-150\text{nm}): 59\% \text{ (FUSE)} \quad 75\% \text{ (Hot)} \]

Manuel Quijada, GSFC
Sep 2014
Al+LiF Mirror FUV Performance Cont..

Manuel Quijada, GSFC
Sep 2014