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Progress toward high-performance astronomical coatings

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Introduction:

University of California Observatories (UCO) has undertaken a program to develop more efficient coatings for astronomical optics. The efficiency of observations generally scales with the rate at which photons are collected, so improvements in reflectivity for mirrors, and better anti-reflection (AR) coatings for transmissive optics has a direct benefit to observational astronomy. Furthermore, if mirror coatings can maintain their maximum performance for longer periods of time, operational costs involved in periodic mirror recoating can be significantly reduced.

The requirements and challenges for astronomical optics are discussed in detail by Phillips et al. (2008)[1], and are briefly reviewed here:

(1) They must be "high-performance", that is, highly reflective for mirrors or transmissive for lenses and windows. For telescope mirrors in the thermal IR, high reflectivity is particularly important to reduce emissivity.

(2) Coatings must be durable, cleanable and stable in their performance for as long as possible, realistically for 4 years or longer.

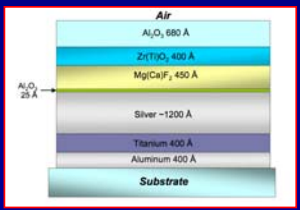
(3) if the coating lifetime is less than that of the optic, we must be able to strip the coating and deposit a new coating without damage to the underlying surface.

Most astronomical coatings have two additional challenges. The first is that they must generally have high-performance over broad ranges in wavelength, e.g., from the atmospheric cutoff to at least the mid-IR (0.31 μm ≤ λ ≤ 12 μm) for telescope mirrors, and either the full optical (0.31 μm ≤ λ ≤ 1.1 μm) or near-IR (0.8 μm ≤ λ ≤ 2.5 μm) ranges for AR coatings. The second challenge is that many astronomical substrates are large, up to 8-m diameter for monolithic mirrors, and ~1-m optics for segmented mirrors and next-generation wide-field cameras.

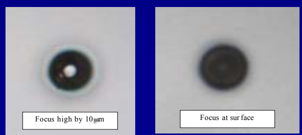
In Phillips et al. (2008)[1], we presented our initial efforts. Here we present a brief update with emphasis on some specific problems.

Protected Silver Mirrors:

In fall 2007 we deposited a Ag-based coating on M1 and M2 of the 1-m Nickel telescope on Mt. Hamilton. This telescope is in regular operation, exposed to the outside night-time environment. The coating was a modified "HG" coating, with an additional layer of Al_2O_3 (figure below). The coating performed satisfactorily for well over one year, but was replaced by a bare aluminum coating in November 2009. By that time, the coating had developed numerous small dark spots (amounting to about 3-4% of the surface), and the scattering had become unacceptable for adaptive optics use. In addition, there were a few spots that appeared "corroded;" these spots had appeared in the first few months and then seemed to stabilize. Nevertheless, after 2 years, the overall reflectivity in the red had dropped by only about 4%, i.e., about the same amount as the degraded surface area. Thus, we believe with some coating modification to reduce the development of the small degraded areas, we should be able too achieve 2-4 years between the need to replace the Ag coatings. We know of two modifications that should help (next).



Modified "HG" coating on the Nickel M1 and M2.



Example of a relatively large silver "spit" at two different microscope focii. The width of each image is about 40 μm. The appearance is roughly consistent with a hemisphere of metal (the bright central spot in the left image is actually an image of the light-filled microscope objective; the small spot just below and left of it is the image of a ceiling light).

We noticed that our Ag-based coatings had a significant number of small scattering centers, which we eventually identified with small globules, or "spits," of silver. These spits are much larger than the film thickness, and adhere only weakly to the surface, so they present points of entry through the protective layers. The problem of silver spitting with e-beam deposition is well known (e.g. Mattox 1998[2]), and we were able to significantly reduce the problem by using a molybdenum liner in the e-gun. Silver is one material for which magnetron sputtering may be a superior deposition process.

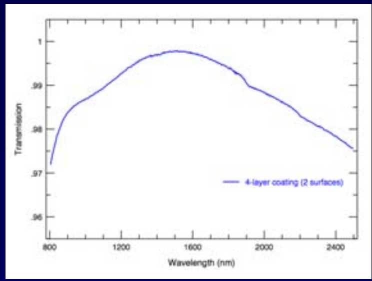
We also studied different base "adhesor" layers under the silver, which are needed because silver bonds poorly to glass. In the traditional HG coating (as well as some UV-enhanced versions of the LLNL coating), aluminum is this adhesor layer. Our tests under high temperature and high relative humidity showed that aluminum corrodes under silver. Depositing a 200Å layer of Al_2O_3 above the Al helps but does not solve the problem. Samples with NiCr or Ti as the adhesor layer showed no deterioration under the same conditions. Thus, the (traditional) adhesor material, NiCr, appears to be the preferred material to use under silver.

Sol-Gel Based AR Coatings:

We reported earlier[1] on optical broad-band AR coatings composed of silica sol-gel and two vacuum-deposited layers underneath, and noted that sol-gel seems to stand up very well to rapid thermal cooling to cryogenic temperatures. Sol-gel is very well suited to the vacuum environment of IR instruments, since absorption of water into the porous coating is obviously not a problem.

We have started investigating actual coatings designed for the near-IR, 0.8–2.4 μm, with encouraging results (see figure right). We plan to conduct a series of tests cycling these coatings between room temperature and a cold vacuum environment to look for any unforeseen problems.

An additional modification we have made to our broad-band sol-gel design is to include a thin layer of Y2O3 to the interface between the substrate and the MgF2 layer. Since Y2O3 is attacked by acids, these coatings are easily stripped by conventional techniques.

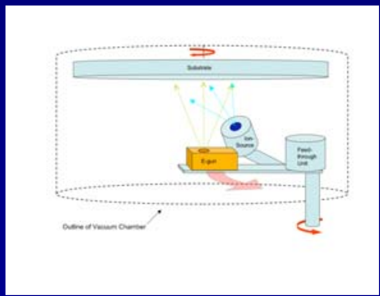


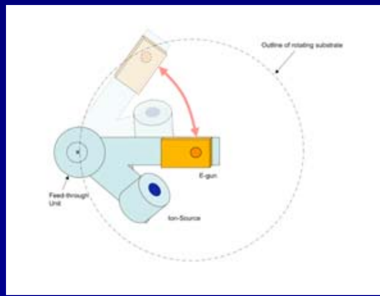
Transmission of fused silica witness sample with the 4-layer sol-gel based AR coating on both sides. (Absorption features in the substrate at 1.38 and 2.22 μm have been removed.)

The future: Major Chamber Upgrades

We intend to upgrade our chamber in the near future with three new capabilities allowing us to explore new materials, compare coating processes, and explore how to coat large optics:

1. Install a large cryopump to increase pumping speeds by a factor of several. This is particularly important to allow reaching the high vacuum levels required to reactively deposit nitrides. Water tends to react with materials to form oxides, so the presence of residual water will tend to produce oxynitrides rather than pure nitrides. The increased pumping speeds of a large cryopump, especially for water, will allow us to reliably deposit nitrides. In particular, we will explore metal nitrides that could replace the NiCr nitride in the Gemini/LLNL coating; NiCr nitride has very poor optical properties and so must be deposited in a very thin layer, but it appears crucial for the formation of a good Si_3N_4 barrier layer above silver.
2. Fabricate and install a "swing-arm" radially-moving stage (figures below). This follows the work of Surface Optics Corporation (SOC), who developed a radially-moving stage used in conjunction with e-beam/IAD to deposit very uniform coatings on large surfaces[3]. Our approach will use a pivoting arm to carry the e-gun and ion source from center to edge of the chamber. This design allows us to move all flexible electrical, cooling and gas lines to the atmosphere side of the chamber; those lines within the chamber are fixed.
3. Installation of magnetrons for sputtering. We will deposit coatings both with e-beam IAD and magnetron sputtering to determine if one process is superior to the other in producing durable coatings.





Side- and top-view schematic diagrams of the vacuum chamber with swing-arm. The rotating substrate is downward facing. The stream of evaporated atoms or molecules from the e-gun (green), mixed with high-energy ions from the broad-beam ion source (cyan), strikes the substrate and adatoms are deposited. As the swing-arm slowly pivots near the edge of the chamber, the e-gun and ion source are slowly moved radially and the coating is "painted" across the entire surface of the rotating substrate. The rate of radial motion is variable and must be calibrated to maintain thickness uniformity in the deposited layer. All service lines (electrical, gas and cooling) pass into the chamber through the rotating shaft of the swing-arm, which is supported by a ferro-fluidic feed-through on the chamber floor. The shaft terminates in a "feed-though unit" which rotates as part of the swing-arm. The inside of the feed-through unit is at atmospheric pressure; the actual vacuum feed-throughs for all lines are located in this feed-though unit. This means that all flexible lines are located outside the vacuum, and the geometry of all components (e-gun, ion source, vacuum feed-throughs and lines) within the vacuum are fixed at all radii on the substrate. The fixed configuration of e-gun, ion source and substrate height permits coating process uniformity for all locations on the substrate; the mechanically fixed lines means the system should be robust to vacuum leaks. (Note that shutter, thickness monitors, baffles and service lines are not shown in this schematic.) During the later phases of the upgrade, the e-gun will be replaced by a bank of magnetrons.

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References:

1. Phillips, A. C., Miller, J., Brown, W., et al., "Progress toward high-performance reflective and anti-reflection coatings for astronomical optics," Proc. SPIE 7018, 70185A (2008).
2. Mattox, D. M., "Handbook of Physical Vapor Deposition (PVD) Processing", Noyes Publications, Park Ridge NJ, 295-296 (1998).
3. Sheikh, D. A., Connell, S. J., and Dummer, R. S., "Durable silver coating for Kepler Space Telescope primary mirror," Proc. SPIE 7010, 70104E (2008).

See also Schwab and Phillips, 7739-66, for more on coatings developments.