Coatings Used in Space

Requirements and Solutions

Author: Samuel Pellicori
Materion Coating Materials News

Optical coatings have been used in discovery, exploratory and monitoring missions since the beginning of space-borne missions. The first application was in the 1958 US launch of the Vanguard satellite in reaction to the USSR Sputnik a year earlier.

Coatings that perform critical optical functions have been used in space instrument applications for the National Aeronautics & Space Administration (NASA), the National Oceanic & Atmospheric Administration (NOAA), and the Dept. of Defense (DoD) for 30+ years. The performance of the first coatings launched into space had been observed to change with time. Investigations seeking the cause of the instability were initiated. Pre-flight testing on the earth's surface in simulated space environments revealed changes in spectral and efficiency performance that are comparable to those changes observed in space. It has been learned that coating layers tend to absorb water in the atmosphere, and when inserted in the vacuum of space, the volatile water leaves. Another effect discovered early was the loss of transmission caused by energetic irradiation from electrons and protons trapped in the radiation belts with equatorial orientation, known as earth's Van Allen belts.

The Space Environment

It is normally considered that the environment of space imposes benign influences on optical instruments and their coatings compared to that of the earth's surface where weather and other environmental stresses are factors. Thin-film coatings employed in the extraterrestrial environment for numerous mission-specific functions have compositions such as:

- Anti-reflective coatings
- Reflectors
- UV to IR band-pass filters
- Thermal control films
- Environmentally-protective coatings

For critical optical coatings, the foundation of environmental performance criteria are the coating test standards in MIL-C 48497: specifically temperature cycling, humid-arid, salt fog, blowing sand, and abrasive wear exposure. Coatings intended for space applications must tolerate and survive a set of environmental requirements that include most of these earth-bound specifications as well as an additional set peculiar to the space environment. Coated optics operate in environments that range from Low-Earth Orbit (LEO) (where the International Space Station (ISS) flies), to planetary and deep space probes. In addition to extended vacuum exposure and damage from micro-meteorite impact, the space environment poses additional radiation and thermal exposure which varies according to the orbital properties of the space mission. Specific to each orbital environment, the ionizing (charged particle) radiation exposure is characterized by the species energy and its density (particles / cm^2 sec = fluence).

In Low-Earth Orbit (LEO) at 400 km altitude, the space environment contains the full spectrum of solar energy, trapped protons, occasional high-energy protons from solar flares and atomic oxygen. High-energy protons can cause optical damage in the form of transmission loss (darkening) through ionization to coatings and optical materials located internally; the other forms are non-ionizing and can affect exposed surfaces and materials such as those on solar-cell power generating panels. Observe that the fluence of electrons is relatively low.

The more distant orbits, Mid-Earth (MEO, 1350 km), Global Positioning Satellites (GPS, 22,000 km), Geostationary (GEO, 35700 km) and High Earth Orbit (various ~100,000 km), are the parking orbits of satellites that carry instrumentation for earth and climate-monitoring, commercial broadcasting, communications, Global Positioning Systems, and military missions. The radiation environment that they are exposed to includes full solar emission, high fluences of trapped electrons, and fewer protons.

Coated internal optics must still be immune to radiation that penetrates the spacecraft instrument's housing. Energies in the MeV range can penetrate mm thicknesses of metals and can create secondary particles. For this reason, spacecraft requirements include a total radiation dose specification that includes energy, fluence, and exposure time, expressed in Rads.

Effects on Optical Coatings

Among the first coatings used in space in 1958 were solar cells to produce power, and emission control tiles to minimize temperature extremes. Both of the first satellites were spherical with reflective aluminum coatings and solar cells. Thick glass tiles with a silver coating on their rear faces were used to control the temperature of the spacecraft. Glass absorbs infrared and re-emits at longer wavelengths providing cooling. The silver mirror doubled the absorption path and thus the emittance while reflecting shorter wavelengths. The first space optical coatings used for band-pass filters were constructed of thermally-evaporated soft materials such as ZnS and MgF_2. Exposure to the space environment containing ionizing radiation, solar UV, atomic oxygen and high vacuum revealed the unstable operation of those coatings. In addition to humid-vacuum shifts in wavelength properties, filters, anti-reflective (AR) coatings and other coatings suffered radiation-induced transmission loss that was especially pronounced at short wavelengths.

The layer thicknesses for coating designs such as AR coatings are of an order of magnitude smaller than the damage range of the energies of the protons and electrons encountered. Therefore, ionization and color-center creation effects from these particles are not the determining factor contributing to radiation damage. However, chemical changes such as reduction and oxidation reaction can induce optical absorption in these layers. Solar UV photons of energies >3eV can induce absorption. Similarly, atomic oxygen is very reactive and can change compositions. Therefore, the solution to the problem of stability in the environments of space is complex and involves many variables.

Through the results of ground simulations, the instability of properties was attributed to the coating materials and their deposition process. Only after high-energy deposition techniques such as E-beam with IAD and reactive magnetron sputtering were developed and matured was it possible to deposit dense, hard and stable metal oxide materials to replace the soft coating materials. Metal oxide compound coating materials possess large energy gaps and provide high transmission to short, near-UV wavelengths because their optical absorption edge is outside (shorter than) the wavelength of interest. Therefore, they are intrinsically less vulnerable to damaging by ionizing and UV radiation. The most commonly used coating materials have become zirconium dioxide ($n = 1.9$), tantalum pentoxide ($n = 2.1$), and hafnium dioxide ($n = 1.9$), all with silicon dioxide ($n = 1.45$).

The introduction of electron-gun evaporation techniques assisted by high energy ions (IAD-EB) produced coated layers with bulk-like packing density and complete oxidation. These are essential characteristics of coatings that maintain stable properties in changing humidity environments and are resistant to radiation. In recent decades, many other high-deposition energy processes have been developed that produce even higher quality thin-film layers. They include magnetron sputtering, ion-beam sputtering, atomic layer deposition, and their many variations. Similarly, new coating materials and preparations have been introduced. Included among the materials advances for both metal oxide and fluoride compounds are improved chemical preparation and starting formulation for pure materials, and specifically prepared mixtures.

The influences of material composition and deposition processes on film layer morphology and stoichiometry have been discussed in previous *Coating Materials News* articles [1]. Deposited layers that possess packing densities and oxidation states that are close to those of the pure bulk materials with low defect and contaminant densities exhibit the highest stability to radiation-induced effects. High deposition energy, as provided by sputtering and ion-assisted techniques, results in high density with the virtual absence of void volume that otherwise could be occupied by volatile water. Development of improved magnetron and ion-beam sputter processes produce the required compact and dense amorphous nanostructure morphology with low defect density and low optical absorption. Now, optical coatings launched on long-term space missions retain their pre-launch optical and mechanical properties.

Space-borne Coating Applications: Solar Cells

A brief discussion follows on the applications of coating technology for providing space power from PV solar cells in commercial, NASA/NOAA, and military satellite instruments. The most visible application of coatings in space appear as large solar panel arrays on spacecraft such as the International Space Station (ISS) that orbits in LEO at ~350 km altitude. The solar panels on ISS have an area of 2,500 sq. m, and generate ~100 kW of power.

The earliest solar cells used in space missions were single-crystal PV silicon that generated current from light of wavelengths 400 nm to 900 nm at ~10 % efficiency. The early cell covers had only a single-layer MgF_2 as the AR coating. That coating proved to have stability problems in long-term operation in all orbits. Because the launch cost per kg is high, lower weight and higher efficiency cells were developed to meet the higher power demands of larger space instruments and provide longer service lifetimes. Today, thin-film multi-layer, multi-junction thin-film semiconductor cells with responsivity from ~320 nm to ~1600 nm and conversion efficiencies exceeding 30 % are used. These cells require coatings that provide a more efficient AR, rejection of UV, survival to temperature cycling, and electrostatic discharge protection (ESD). Exposure time to the solar energy is ~60% in LEO, and between exposure and eclipse, the covered cells undergo thousands of temperature cycles ranging from ~150° C to -150° C. Following is an illustration of a generic solar cell component of a typical space power solar panel.

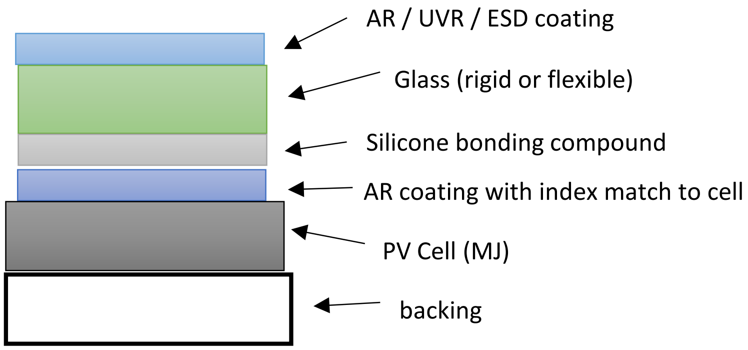

Figure 1. The components of a typical space solar cell showing the locations of critical coatings.

The coating on the incident surface is a complex multi-layer design that functions to reflect UV wavelengths that would otherwise damage the silicone cement and glass. It also provides low reflection loss over the multi-junction cell response for maximum photon transfer from ~320 to >1600 nm. A transparent conducting oxide layer (ESD) is included to drain off electrical charge that otherwise will accumulate and discharge as damaging arcing [2]. Individual solar cells are covered with a cover glass that protects against UV, proton and electron radiation, atomic oxygen exposure and micro-meteorite bombardment.

Not only is the correct choice of materials important for resisting the space radiation environment, but the deposition process is equally important [2]. Figure 2 shows the transmittances before and after radiation of a UVR/AR coating produced by Optical Coating Solutions (Camarillo, CA). The comparison between this coating deposited by E-beam and pulsed DC magnetron sputtered processes is clear: the PDCMS process produces superior resistance to the environment that simulated the proton radiation spectrum experienced in the GPS orbit.

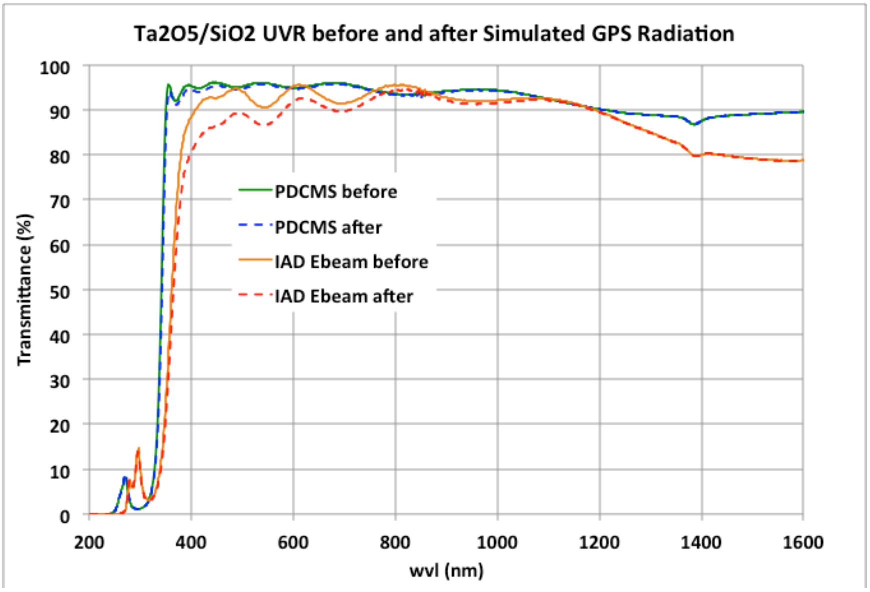

Figure 2. Stabilities of a UV reflecting, wide-band AR coating used on space solar cell covers exposed to simulated GPS radiation. The pulsed DC magnetron sputtered coating exhibits superior stability compared to the e-beam deposition process.

The cover glass can be a rigid glass or the newly introduced silicone-based flexible cover, and is cemented to the PV cell with a silicone compound. Glass of thickness ~150 µm is commonly used. The addition of a 1-3 % cerium oxide renders stability against darkening to ionizing radiation. The Ce^{3+} ions inhibit the formation of radiation-induced vacancy-related defects that cause absorption. The trade in using Ce-doped glass is for lower transmission of near-UV energy. The wider spectral response of multi-junction cells is adversely affected by the current loss that would otherwise be generated by their top junction, which has a bandgap that extends to the near-UV wavelengths short of 400 nm. For this reason, silica-based cover glasses are preferred.

The refractive index of the cell's semiconductor material is high, ~3.3. The cell is bonded to the cover glass with a low-index (n = 1.43) silicone compound and it must be optically interfaced with a multi-layer coating be to prevent reflection loss. An index-matching coating is therefore applied to the cell during its manufacture.

The cover and all its coatings need to resist darkening in the ionizing and UV environment in all orbits, and additionally atomic oxygen in LEO. Stable coating materials and optimum deposition processes have been developed that extend the lifetime in space to the point where end of life (EOL) is ≥90% of their beginning of life (BOL) efficiency. This enables longer operational life between expensive replacement cycles [2]. The following shows an example of a solar panel array consisting of hundreds of individual cells. Three panel assemblies are shown deployed in the on-orbit configuration.

Figure 3. A solar panel "wing" made by Orbital ATK in its unfolded extent.

Complex Many-Layer Coatings for Outer Space Applications

State-of-the-technology coating processes for all space missions employ stable hard-oxide materials deposited by high-energy processes. Questions about space-environmental stability of multi-layer coatings that historically haunted designers and engineers of space instrumentation have thereby been put to rest. The performance record includes the continued successful operation of Landsat, MODIS and subsequent high-reliability instruments for earth resources, ocean color, and climate monitoring. The missions that these instruments perform require band-pass filters located at wavelengths from ~400 nm to 12 µm. The absolute changes in scene radiance are measured over time intervals and location (for example weather patterns), therefore the system responses in the pass-bands must be stable. As a check, an on-board radiometric monitoring system is periodically referenced. It has been determined after many studies of this "stability monitor" that it is difficult to separate changes in true system response from changes in the stability monitor.

Based on space simulations, the stability of modern optical coatings probably exceeds the stability of other components in the instrument. The complex multi-layer (sometimes including ~100 layers) coatings on board exhibit negligible spectral shifts between atmospheric and vacuum conditions, are resistant to ionizing radiation and atomic oxygen exposure. They suffer <0.1% wavelength shift due to thermal excursions. Spectral changes in the center wavelength (CWL) for MODIS band-pass filters have been measured to be <0.5 nm between pre-launch and on-orbit 5-year orbital conditions. On-orbit changes measured during the first five years of operation are <0.1 nm in the CWL for individual pass-bands between 400 nm and 1000 nm where the greatest improvement has been achieved due to the advancements in coating technology.

Figure 4: Orbital ATK UltraFlex Solar Array/Phoenix Lander on Martian Surface. Photo Credit: NASA

The resistance to radiation-induced changes in the near-earth radiation orbital environments has been demonstrated. Beyond earth-orbiting applications, planetary and deep space missions face a more intense radiation environment. This includes charged particles of higher energies that are present in transition from altitudes within earth's trapped radiation belts to deep space journeys to planets that possess even more intense radiation belts such as Jupiter. Instruments that land on the surface of Mars operate without the protection of a UV-absorbing atmosphere. Additionally, their window and lens coatings must be immune to abrasion and the collection of wind-blown dust. Those windows are AR coated and include an electrostatic dispersive (ESD) coating in the form of a transparent conducting oxide (TCO) layer. The traditional ESD TCO is ITO. However, AZO and other TCO materials are being explored as replacements for ITO to provide better stability [2].

Conclusion

The refinements in coating materials and processes has progressed over the past decade. This has resulted in the ability to produce complex multi-layer optical coatings with high stability to meet the challenging environment of space missions. These advances benefit the space program with longer operational lifetime, higher efficiencies, and lower costs for its multiple scientific, commercial, and military applications.

For information on Materion's advancements with optical coating materials for space environments, visit their website.

References for Further Reading

1. *Coating Materials News* assorted technical articles, http://materion.com/ResourceCenter/Newsletters/CoatingMaterialsNews_Articles/CoatingMaterialsNews.
2. Pellicori, Samuel, Carol L. Martinez, Paul Hausgen, and David Wilt, "Development and Testing of Coatings for Orbital Space Radiation Environments," *Applied Optics*, V 53 N 4, A339-A350, 2014.

Principal Contributor
Samuel Pellicori, Pellicori Optical Consulting, Santa Barbara, CA
Phone: 805.682.1922, Email: pellopt@cox.net

Material Advanced Materials Group is a global supplier of premier specialty materials and services. Our offerings include precious and non-precious thin film deposition materials, inorganic chemicals and microelectronic packaging products. In addition, we offer related services to meet our customers' requirements for precision parts cleaning, precious and valuable metal reclamation and R&D. We support diverse industries including LED, semiconductor, data storage, optical coatings, large area glass and aerospace.