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High-Efficiency Solar Coatings

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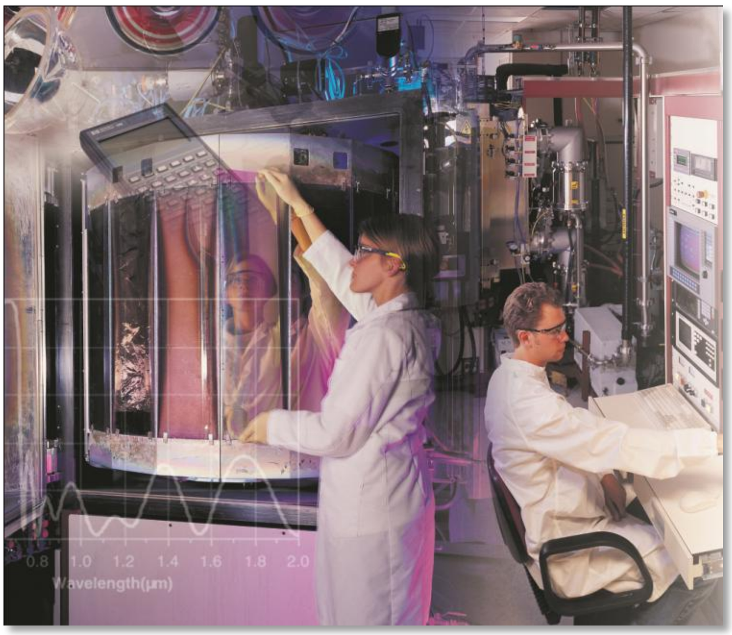

Image courtesy of Deposition Sciences, Inc.

Thin films and thin-film technology have played an important role in photovoltaic (PV) power generation for terrestrial and space-qualified applications. Traditionally, the top layer of solar cells has been a thin cover glass, coated with a conventional anti-reflection (AR) coating. This cover glass has served as a radiation barrier, as an optical-coupling element, and as a protective agent against debris, impact and other environmental aggressors. Thin-film coatings are, therefore, critical to the performance and environmental robustness of PV systems.

Solar cell construction

Functional PV materials are engineered to maximize the conversion of every photon in the solar spectrum into charge carriers. Materials ranging from crystalline silicon (c-Si) to thin-film-based amorphous silicon (a-Si), and from copper indium gallium diselenide (CIGS) to III-V compounds are commonly used. Solar cell designs range from single-junction silicon to inverted multi-junction, and from monolithic to multi-element construction. Systems can be terrestrial (AM 1.5) or space- (AM0) based; the former being divided into one-sun systems and concentrator systems (5-1000 suns), which use lenses and/or mirrors as primary light collectors.

As the technology for solar cell construction has evolved, so has the need for thin-film coatings, both simple and complex, used on system elements like lenses, collectors, mirrors and the cell itself. Customizable AR coatings applied to lenses or as top-layer on the cell increase the photon flux reaching the PV medium, while reflecting part of the incident energy that nets only unwanted cell heating. For multi-junction cells, this AR coating can further tailor the spectral response in order to match the currents at the different junctions. Viewed this way, the AR coating can be thought of as a multi-purpose spectral/current regulation coating.

> **"Broadband, highly reflective layers are needed for solar collector and solar concentrator applications."**

High-efficiency solar AR coatings

The efficiency of a PV solar cell can be quantified by a number of metrics, but one of the most important ones is the external quantum efficiency (EQE) of the device. Whether a PV cell is single-junction or multi-junction, its EQE is a function of the flux of photons reaching the PV medium. It is, therefore, essential to optically match the PV cell to the incident medium in which it operates (air/space). This inevitably requires the addition of one or more interfaces between the solar cell and the incident medium-- in the form of AR coatings.

The design of any AR coating can be simply characterized by the irradiance, emittance and absorptance of the sources and media in which the AR will operate. It can also be characterized by the optical properties, index of refraction and extinction coefficient, of the coating materials and substrates used in the optical system. The spectral band over which the coating must operate defines the anti-reflection problem. For PV solar cells implies the solar spectra.

The inputs to the PV device are the solar spectra, represented by the ASTM G173-03 standard with terrestrial solar spectral irradiance on a specifically oriented surface under one set of atmospheric conditions. These solar spectra are shown in Figure 1. These curves establish the envelope for integrated photon input to the PV medium in the functional 300-2500nm band. Approximately 5% of the solar spectrum falls in the 1900-2500nm range, but this spectral region is normally non-operative since it consists mostly of unwanted heat. Effectively, an optimized broadband solar AR should operate in the 300-1850nm band.

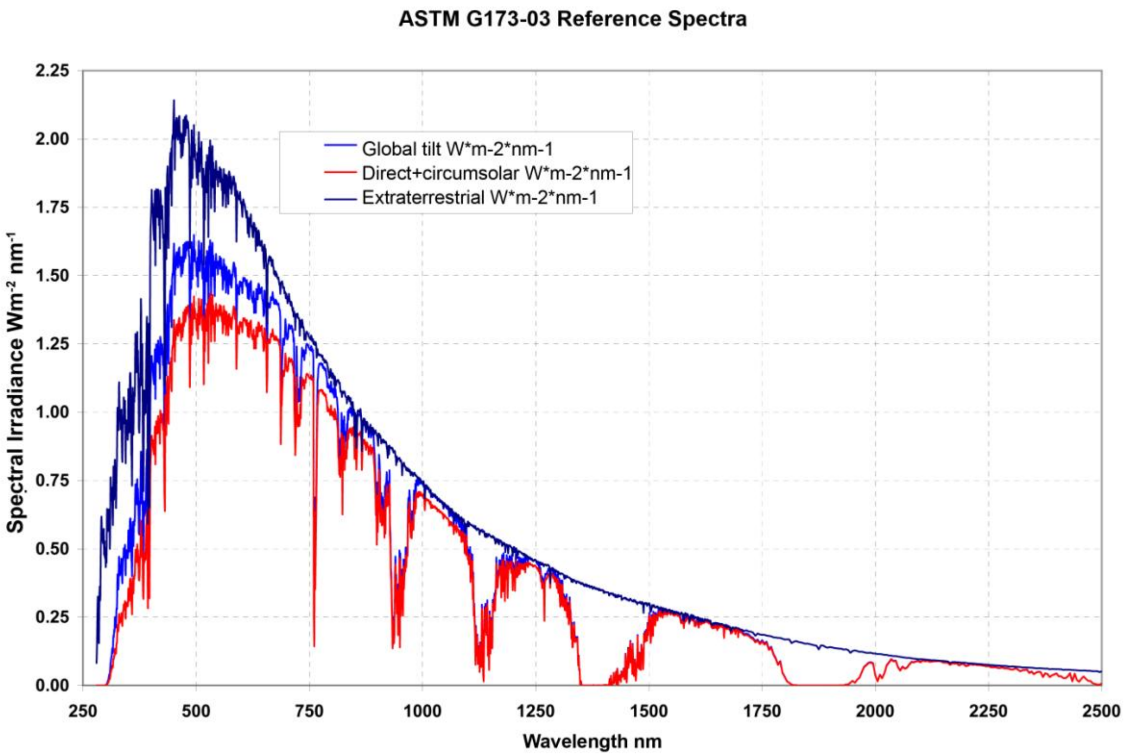

Figure 1: ASTM G173-03 solar spectra

The design of a functional BBAR for solar cell systems must take into consideration the optical properties of the PV materials and the complementary optical thin films. The front surface Fresnel reflectance for any interface can be calculated following the relationship:

$$R = [(n_{material} - n_{medium})^2 + k_{material}^2]/ [(n_{material} + n_{medium})^2 + k_{material}^2]$$

For the majority of the III-V elements and compounds, the index of refraction falls in the $n_{material}$ = 3.0-5.0 range. This results in front-surface reflectance losses (in AM 1.5) somewhere between R_{max}~25 – 45%.

By designing a robust multi-layer BBAR that is matched to the AM 1.5 solar spectrum, we have been able to reduce the front surface reflectance to R_{avg} =< 3% over the 300-1850nm operating band. Figure 2 shows the reflectance of a typical multi-junction solar cell with and without an AR coating applied.

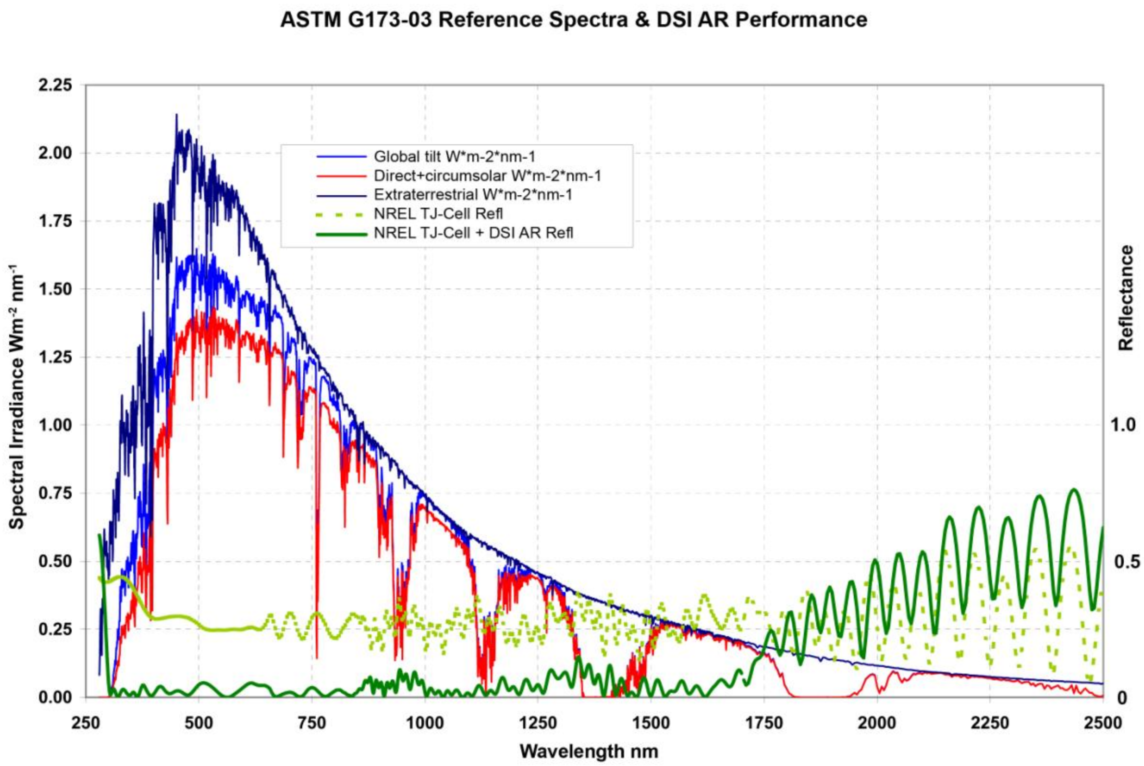

Figure 2: *Uncoated and coated specular reflectance of LM triple-junction solar cell overlaid with ASTM G173-03 Solar Spectra.*

Modeling has shown that the application of a multi-layer BBAR can result in a 3-5% gain in the EQE for multi-junction solar cells (under 500x concentration), when compared to the EQE of the same cell using a conventional V-coat AR. This performance gain in cell efficiency makes it possible for commercially available solar cells to breaking into the 40 – 50% conversion efficiency range. This is significant in that this type of performance has been observed only with sophisticated solar cell construction in the laboratory environment.

Broadband, high reflecting coatings

Broadband, highly reflective layers are needed for solar collector and solar concentrator applications. Typically, the metallic materials used to obtain high reflectivity were either aluminum or silver. Silver is preferred for solar applications due to its high reflectivity even though this reflectivity falls in the blue and ultraviolet regions of the spectrum. A well-known method to improve the reflectivity of silver is “enhanced silver.”This consists of an optically thick silver layer onto which dielectric layers are deposited to improve the silver’s reflectivity in the blue (around 450nm) from 90% to above 95%.

Conventional enhanced silver coatings require a silver layer between 100nm and 600nm in thickness. Deposition Sciences, Inc. (DSI) in Santa Rosa, California has developed a new coating called EcoWhite Silver (patent pending) that uses considerably less silver (generally, 80nm or less) and achieves higher reflectivity in the blue wavelengths than traditional silver coatings.

Solar energy collection depends on reflecting large parts of the solar spectrum. The solar spectrum at ground level contains significant energy in the range from 350nm to about 2500nm. Increases in reflectivity in this region can increase the overall efficiency of a solar power system.

Solar concentrator systems use multi-junction solar cells, which, as previously mentioned, exploit the solar spectrum from about 350nm to about 1500nm. Due to the available types of semiconductor materials, there is a particular need for very high reflectivity in the short wavelength region of this range, from about 350nm to about 450nm. If insufficient light is available in this wavelength range, the semiconductor junction responsible for converting this light will become reverse-biased, limiting the power output of the other junctions in series.

Thus there exists a need for a low-cost reflector coating that has high reflectivity over the range 350nm to 1500nm for concentrated solar PV applications. DSI’s reflector coating with high reflectivity is comprised of a thin layer of aluminum, followed by a thin buffer layer, followed by a thin layer of silver, followed by capping and enhancing layers. As mentioned above, relative to conventional enhanced silver coatings, the new coating uses less silver, has higher blue reflectivity and has high durability.

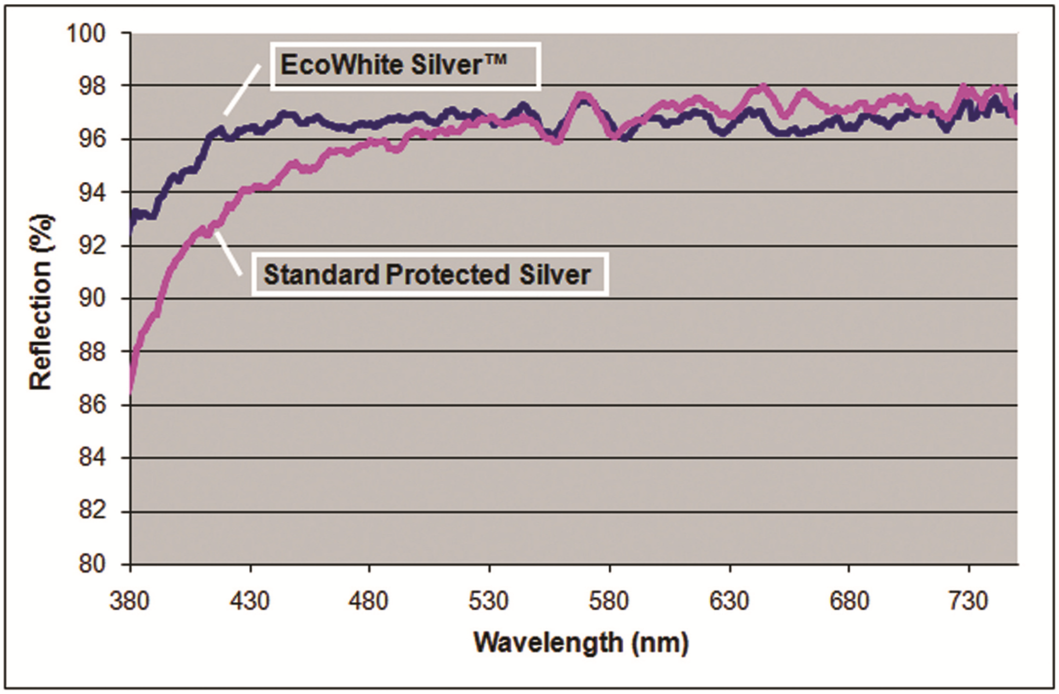

Figure 3*: The reduction in blue roll-off using EcoWhite Silver coatings, as compared to standard protected silver coatings, saves material, reduces costs and results in better performance.*

Summary

As attempts are made to reach ever higher collection and conversion efficiencies for commercial CPV systems, thin-film optical coatings play an increasingly important role in the performance of both collection optics and cell-level performance. DSI, in collaboration with the National Renewable Energy Laboratory (NREL), are developing environmentally stable, ultra-durable BBAR coatings for multi-junction metamorphic and lattice-matched solar cells. These coatings have demonstrated as much as a 5% relative gain in the conversion efficiency of solar cell devices.

The role of thin-film coatings is expected to continue to grow as the worldwide move from consumable to renewable energy continues to accelerate.

About the authors

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