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Solar Cells Need Coatings Also

This quarter's CMN discusses two topics, which are intimately related. We take a cursory look at solar cells and their coating requirements. Optical coatings perform two functions on solar cells: electrical contact and reflection reduction. Economy of manufacture plays a role, and the current trend is the substitution of ITO with AZO for the transparent conducting contact on all types of solar cell. The introduction of AZO to other applications is also presented, and preliminary tests of a new AZO target material are included.

The requirements for solar cells are divided between two major applications: terrestrial and extraterrestrial. The primary requirement for extraterrestrial power generation is maximum output/weight, while that for terrestrial applications is maximum output/$. Crystalline silicon (c-Si) has been the material most used for photovoltaic conversion of solar photons to electric current. A c-Si cell has a single junction for charge generation, and with its simple construction produces efficient conversion. Variations on single-crystal Si are amorphous thin film (α-Si) and polycrystalline Si forms. The latter compositions are more economical to produce than c-Si cells, especially for large areas and flexible substrates. The efficiencies of thin-film cells are lower than c-Si because of the abundance of defects and boundaries that present barriers to charge lifetimes and mobility. The power output of terrestrial based solar cells where weight is not a limitation can be multiplied by the use of optical concentration. Less silicon material is used when the sun's image is focused to a small area. The new problem is to dissipate the heat, which lowers conversion efficiency.

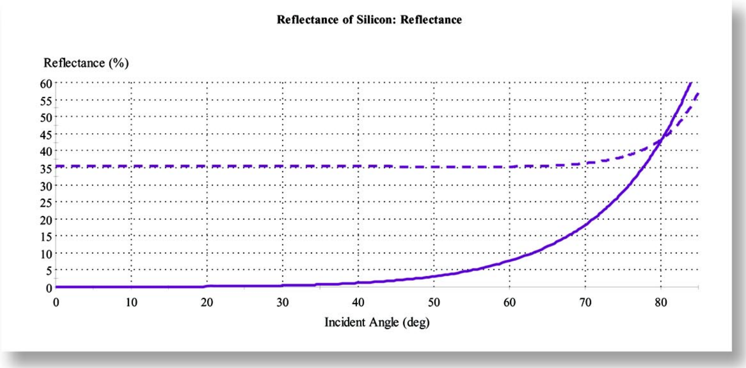

Figure 1. Reflectance of uncoated (dashed) and coated (solid) silicon vs incidence angle. Wavelength = 600 nm. This incidence-angle effect is responsible for the fact that lenses used in digital photography are designed to focus telecentric beams.

Approximately 95% of solar energy reaching the top of the atmosphere is contained between wavelengths ~300 nm and 2500 nm. Compound semi-conductor thin-film compositions for multi-junction solar cell constructions have been developed to extend the cell's response beyond that provided by silicon. The multiple-junction construction employs staggered bandgaps of the semiconductors to maximize the conversion of the solar spectrum to electrical power. Some of these compound compositions are: CdTe/CdS, Cu(InGa)Se_2 known as CIS or CIGS, three-junction: InGaP/GaAs/Ge, and so on to as many as 5-junction structures that respond to nearly 2000 nm.

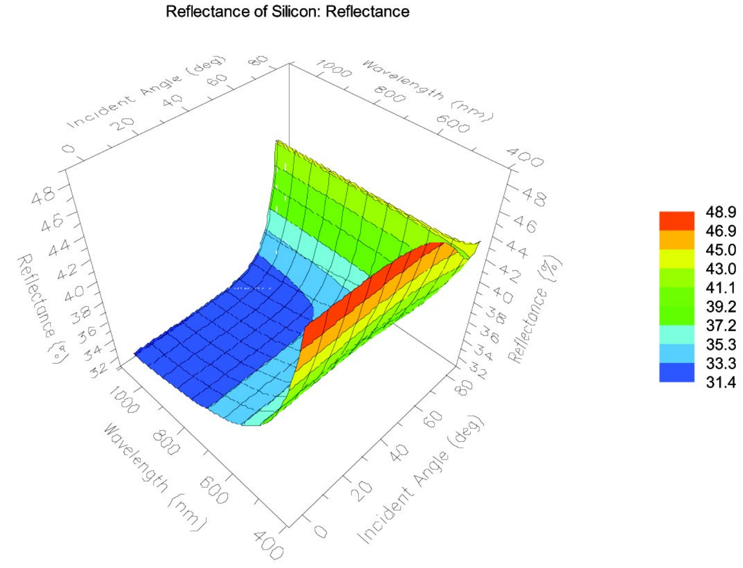

Figure 2. Reflection of a bare silicon surface vs wavelength and incidence angle.

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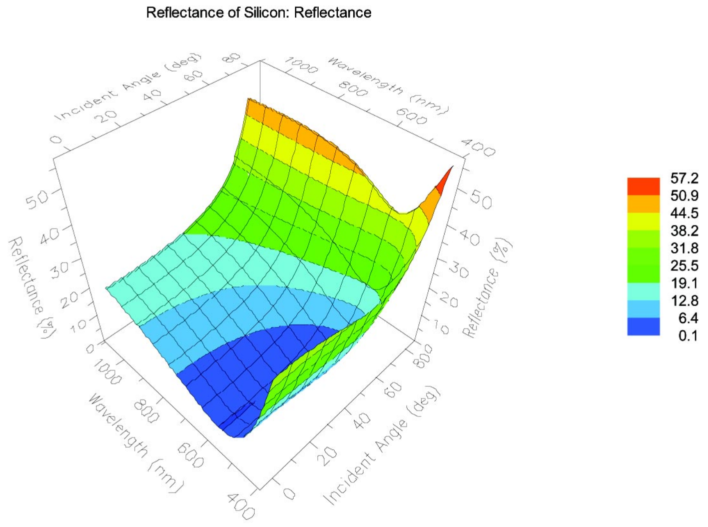

Figure 3. Reflection of silicon after coating with a QW of Silicon Nitride at 600 nm is low over a small area, but remains high at short- and long- wavelengths and large incidence angles.

Semi-conductor PV materials have refractive indices of 3.5- 4 in visible light wavelengths. The surface will reflect more than 35% of the incident energy unless coated for reflection reduction. Figure 1 shows the uncoated and single-layer AR-coated reflectance from silicon at wavelength 600 nm. Figure 2 shows the uncoated reflectance from silicon vs. wavelength and angle; Figure 3 shows similarly the reflection reduction produced by a single layer of silicon nitride, the coating material commonly deposited in the silicon foundry.

The result of the single QW coating is to admit up to 35% more energy into the silicon to become available for a corresponding increase in photon-to-carrier conversion efficiency.

Note in Figure 3 the significant increase in reflection loss at large angles. This is the reason why lenses for digital cameras are different than those used for film cameras. Film emulsion has about equal response out to very large angles, while with silicon, unacceptable shading is present due to loss at the large angles. Digital lenses are designed to present light rays to the CCD or CMOS array at near perpendicular angles, thereby avoiding the fall off in brightness at the edges of the frame. Note also that this shading effect is significant for wide-angle lenses, but that “normal” film lenses could still be used for small-angle (long focal lengths) on digital cameras without noticeable degradation.

It is obvious that solar cell energy conversion efficiency can be inexpensively increased with the use of AR coatings that are designed for wide-angle and wide-band performance. Such coatings have been used for high-value applications such as spacecraft power sources for many years [1].

The semiconductor PV materials require electrodes to collect the electron current, and they typically sandwich the junction materials, so the incidence side needs to be transparent to the energy. Traditionally ITO (Sn-doped Indium Oxide) serves this purpose, but AZO (Al-doped Zinc Oxide) and its variations are becoming replacements for ITO.

AZO Transparent Conductive Coating Material

Past CMN issues have discussed transparent conductive oxide (TCO) materials, emphasizing ITO as being the most common TCO in use. We have also discussed the trend to replace ITO with alternative TCOs, and AZO is receiving the most attention currently [2]. ITO is Indium Oxide doped with 2% to 20% Tin. AZO is Zinc Oxide doped with 1% to 4% Aluminum (sometimes denoted ZAO). For both TCOs, the dopant can be introduced in metallic or oxide-compound form, as determined by the sputter target composition. The composition is tailored to the required application parameters: electrical resistivity, or optical transmissivity and reflectivity. We have reviewed the many applications for TCOs in past issues of CMN; the most well known include: flat panel display and solar cell electrodes, thermal control windows, RF and EMI shielding, and gas sensors. Several instructive articles on these topics have been written by Dr. Peter Martin [3]. Table 1 summarizes the most common applications for TCOs and their approximate electrical and optical properties.

TCO compositions based on Zinc Oxide are being developed as a more economical (by ~30%) and resource-abundant material

Table 1

Application	**Sheet Resistance (Ω/sq)**	**Visible Transmission (%)**
RF / EMI Shielding	~5	~80
Touch Panel Contact	<50	~85
LC Display Electrode	<500	~85
Thermal Control windows	~10	>80
Solar Cell Contacts	~100	>85
Static Charge Drain	Many 1000’s	--

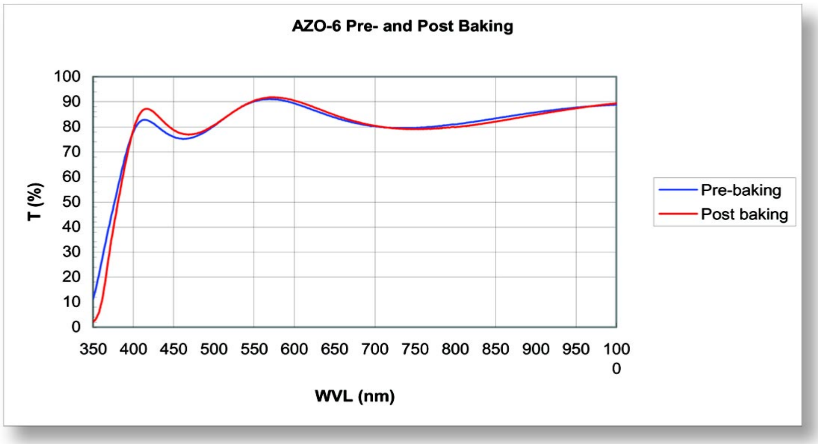

Figure 4. Results of high-temperature air-baking of 305 nm thick AZO layer on a glass substrate. Sheet R increased from 440 Ω/sq to >1 M Ω/sq.

than Indium-based TCOs. The coating industry is adapting substitute Zinc Oxide based materials to large volume applications such as solar cells, display panels, and thermal-control architectural windows. In the solar cell industry, the transparent electrode through which solar energy passes on its way to the active cell can be economically deposited in large-area sputter systems to coat thin-film and crystal solar cells of different compositions.

ZnO can be doped with Al-metal, or with Al_2O_3, In, Sb, Gd, and other donors. Doping with Aluminum results in films with the highest transmission for optical applications. It is reported that the addition of H to the plasma has resulted in higher transmission and better environmental stability [4]. An advantage that AZO films provide over ITO is that pattern etching in AZO films can be achieved using weak acids of <1% concentration (0.2% HNO_3 for 2 min at 18° C), and therefore is an easier process than required for etching ITO films [5]. The etch rate is somewhat dependent on film crystallinity.

Useable AZO films cannot be deposited by using thermal (resistance-heated or E-beam) evaporation; sputtering is the technique required. If the sputter target is non-conducting, as with a ceramic composition, RF sputter techniques are necessary; otherwise reactive DC magnetron sputtering is preferred.

Williams Advanced Materials* has produced a conductive high-density AZO target with which Tom Ives, Director of Technology at Thin Film Technology*, has been processing AZO films using DC magnetron sputtering. (*TFT and CERAC are subsidiaries of WAM). The wt-% composition of the target is 2% Al / 98% ZnO. Preliminary results have demonstrated good process stability and low absorption. Rates between ~5 and ~12 nm/min with power densities 2-3 W/cm^2 have been tried to date, and sheet resistances between ~50 Ω/sq. and several K Ω/sq. have been deposited on glass and IR materials. Films deposited on cool substrates exhibit a larger instability to post-deposition in air than films deposited on substrates near 300° C. When a 300 nm thick AZO layer was heat treated in at 400 C for 2 hrs to determine the max transmission achievable (see Figure 4), the film was

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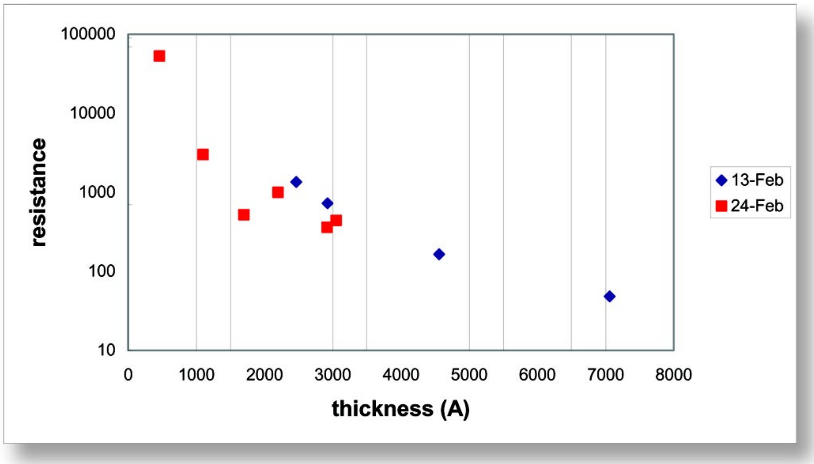

Figure 5. Sheet resistances vs thickness for AZO deposited at 3.4 W/cm^2 (24 Feb points) and ~2.2 W/cm^2 for others except lowest R at 4.75 W/cm^2.

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completely oxidized, and its initial sheet R ~500 Ω/sq increased and approached a terminal value of 1.5 MΩ/sq. Post air-baking transmission increases because the absorption decreases, as shown. The extinction coefficient at 400 nm decreased from 0.010 to 0.006.

The refractive indices for reactive magnetron sputtered AZO at 600 nm wavelength range from 1.90 to 1.93. Pulsed DC magnetron sputter deposition of AZO produces an index ~2.00 to 2.05, comparable to DC magnetron sputtered and E-beamed IAD ITO.

Figure 5 presents the sheet resistances achieved for several DC magnetron depositions made with the Williams 2%/98% target.

Sheet resistances near10 Ω/sq have been obtained with 500 nm thick films using mid-frequency magnetron sputtering of a target composed of 1.5 wt % Al. Substrate temperatures between 150° to 200° C and high rate deposition were required in that work [6].

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