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Thin Film Photovoltaic Solar Cells

Solar Energy and Cell Response

The generation of solar electric power considers the available solar energy spectrum and the efficiency of converting solar photons to electric current. Efficient conversion requires matching solar cell sensitivity response to the solar spectrum reaching the Earth's surface, i.e., the ground-level solar irradiance as it is transmitted by the atmosphere. The optical path at noon at the equator is defined as 1 atmosphere (AM1). An average path length over typically collected sun exposure angles is closer to 1.5 – 2 atmospheres. Figure 1 shows the spectral irradiances for top of the atmosphere (AM0) and through 1.5 atmospheres at Earth's surface [1]. The AM1.5 model has been adapted by the solar industry for evaluating solar cell modules, and is used by the National Renewable Energy Lab (NREL) as a test bed.

Figure 1

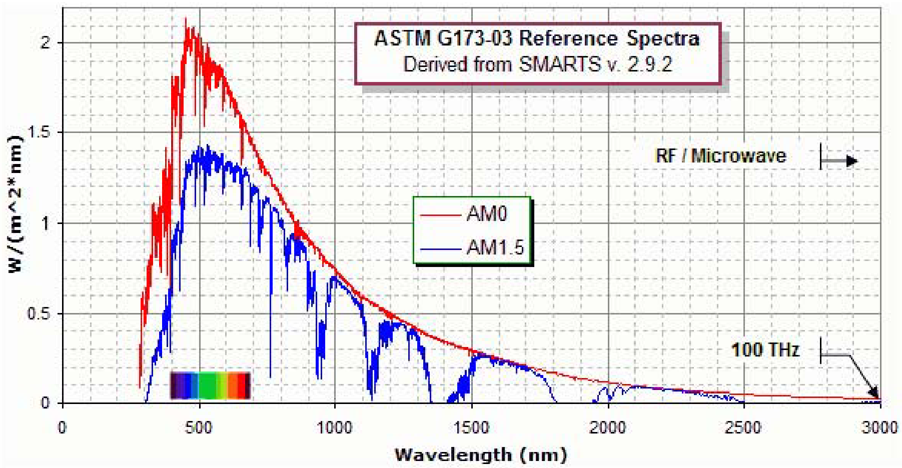

Figure 1. ASTM solar spectral irradiance at top of the atmosphere and at the earth's surface through Air Mass 1.5 [Ref 1].

Atmospheric absorption (ozone, water vapor, etc) and scattering by aerosols eliminate solar terrestrial energy at wavelengths shorter than ~350 nm, and impose absorption bands in the irradiance spectrum. Glass covers also absorb below 320 nm. Most of the solar irradiance energy distribution is at wavelengths short of ~1000 nm, where Silicon-based and CdTe materials absorb highly and possess high conversion efficiency. Special materials and layer combinations have been developed to extend the spectral response to collect more energy and thereby increase efficiencies. Figure 2 (see page 2) shows the spectral responses for different solar cell materials [1].

Spectral bandwidths for materials are: amorphous silicon α-Si:H, 400-650 nm; μ-Si:H 650 – 850 nm, so layered the response covers 400 to 850 nm. CdTe cells respond over 400 – 850 nm with higher quantum efficiency than Silicon compositions. CIGS (CuInGaSe/S) cover 400-1100 nm. These are discussed further in the following sections.

Contents

Silicon-Based Solar Cells

The photovoltaic (PV) solar cell is undergoing rapid development and commercialization as a source of renewable energy. The Solar America Initiative (SAI) program under the direction of the Department of Energy has as one of its goals the increase in solar power generation for commercial and residential energy needs at a greatly reduced $/KWhr cost. Achieving this goal requires greater conversion efficiencies continuing research and development of materials and processes. The first high efficiency PV cells were made from single crystal silicon ("first generation" technology). Ribbon silicon generated by polycrystalline or amorphous growth technology has lower production cost at the sacrifice of lower light-to-electric current conversion ef-

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ficiency. Silicon-based technology has a fundamental conversion limitation due to its relatively narrow spectral absorption width, ~400 to ~850 nm even with the compound structure mentioned above. This range captures only ~50% of the total available solar terrestrial irradiance for wavelengths <1500 nm. The classical solar cell based on crystalline silicon, achieves conversion efficiencies near 20% and this technology accounts for perhaps 95% of current module installations. However, physical limitations drive production costs. Crystalline silicon has a relatively low absorption of visible and near-IR energy, therefore thicknesses of at least 150 μm are required to obtain efficient PV output. Handling and processing of thinner silicon is also inhibited by fragility issues of large area wafers. Cell size (area) is restricted by practical and economical limitations associated with the production of large diameter wafers from crystal ingots. Solar concentrator optics are being employed to increase the efficiency per unit area, thereby permitting smaller areas of silicon to be used. Such optics are also used with the other thin-film materials discussed below.

Figure 2

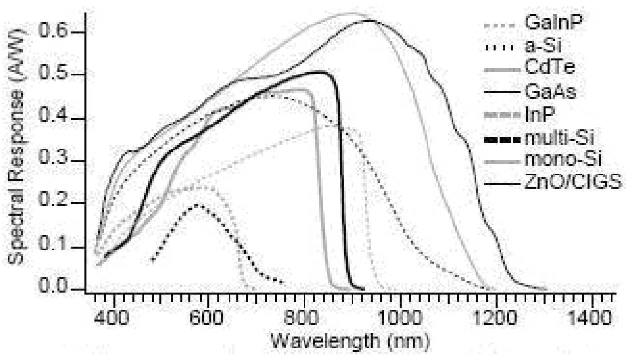

Figure 2. Spectral responses for various solar cell materials [1].

Thin Film Development: "Second Generation" PV Cell Technology

Thin-film PV (TFPV) cells are under development by several companies in Europe and the US. New compositions based on thin-film structures have overcome the limitations of crystalline silicon specifically by producing high absorption and efficient conversion over a larger portion of the solar spectrum in thicknesses of a few micrometers. Large area modules can be economically produced using roll-to-roll vacuum web coating processing on non-rigid substrates. This "second generation" technology is capable of producing cell efficiencies greater than crystalline silicon because of their extended spectral response, and they are more economical to produce in high volume. Production-line modules currently achieve typical efficiencies ~14% [3]. The lower efficiency compared with crystalline silicon is traded against the larger area in light of the lower production cost of TFPV cell.

Compositions of the solar photon absorbers in TFPV modules include: amorphous silicon (α-Si:H), micromorphous silicon (μ-Si) and vertically stacked layers of both, and multi-junction α-Si /α-Ge. In the CdTe TFPV cell, the light absorbing layer is CdTe 10 μm thick and the CdS heterojunction 0.1 μm thick (Figure 3). Both layers can be deposited by evaporation or CVD.

For compound materials, Copper Indium Sulfur/Selenide (CIS) and CuInGaSe/S (CIGS), the absorber thickness need only be ~2 μm, leading to lower materials cost and introducing a variety of fabrication processes. CIGS cells with efficiency ~20% have been fabricated. TFPV cells are constructed of multiple layers as modules, then divided into cells as shown in Figure 3. Between the transparent conductor (TCO) and the back metal contact are buffer and absorber layers. The fabrication process, and therefore the illumination direction, determines the order in which these layers are deposited, as illustrated. The absorber / conversion layer can consist of a stacked series of multi-layers of controlled composition to expand the spectral absorption range and thereby increase

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Thin-Film Solar Cells: Advances Beyond Silicon

In an effort to circumvent the materials resource limitations and production costs associated with the first generation silicon technology, effort is being applied toward the development and production of PV cells based on advanced technologies. Multi-junction cells built of thin layers of III-V composition and with their wider spectral response have achieved twice the efficiency of silicon cells under 10X solar concentration [2]. Structures having 3 and 4 junctions provide spectral response from UV wavelengths approaching 1500 nm. Multi-junction cells are fabricated in low volume under high production cost, and find application in orbiting space platforms where weight/kW is a significant cost and payload capacity factor. Deposition processes use expensive equipment such as MOCVD (Metal-Organic Chemical Vapor Deposition) or MBE (Molecular Beam Epitaxy).

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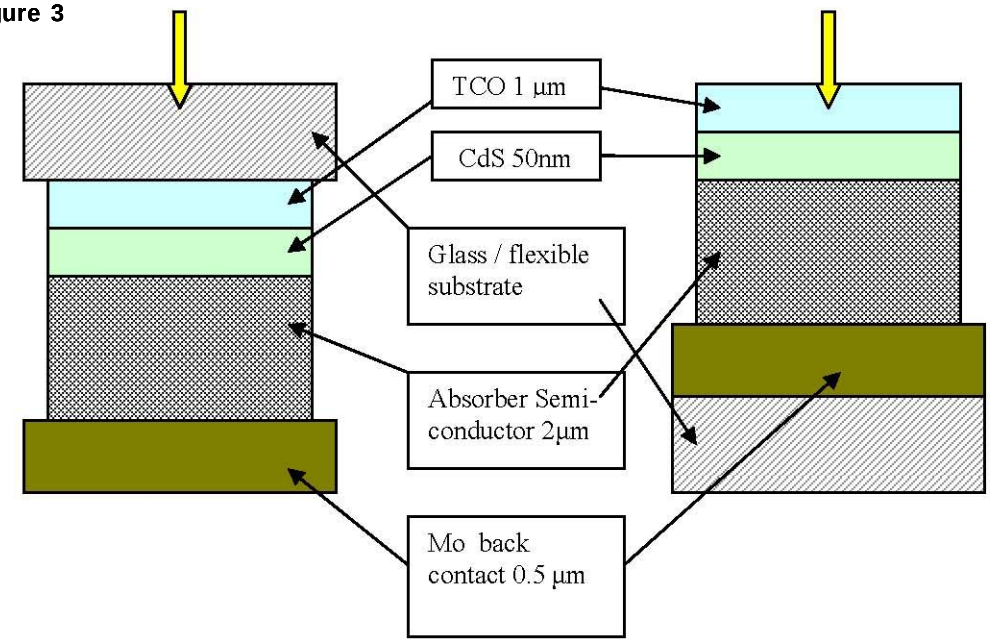

Figure 3. Alternate configurations for TFPV solar cells. With the construction on the right, the substrate can be a flexible metal such as Kapton, polyimide film or stainless steel foil, in place of glass.

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the cell conversion efficiency. Process temperatures for the CVD of CIGS and CIS absorbers range from 400 to 600°, necessitating the presence of barrier layers to prevent diffusion of metal impurities such as Fe that will reduce conversion efficiency. For example, if the cell is grown on a stainless steel foil substrate, a diffusion barrier is needed between the steel and the Mo conductor. That high-dielectric barrier often is a several-µm thick layer of an oxide such as SiOx. Greater stability to years (actually decades) of exposure to the environment in terrestrial installations is a concern that is receiving attention. Improved barrier or protective coatings and greater tolerance to temperature and humidity cycles are needed. The second-surface construction (left) in Figure 3 provides better immunity to environmental effects.

The TCO used with TFPV cells is Al:ZnO (AZO), a more economical alternative to ITO with higher transmission. We have discussed AZO coating material previously [4]. TFPV cells and modules are built using high temperature PECVD, or by plasma-enhanced evaporation, sputter deposition, and other techniques. DC and pulsed-DC magnetron sputtering is commonly used to deposit all of the layers from TCO to Mo shown in Figure 3. Evaporation of Cu, In, Ga, Se, and CdS or sputtering of CuGa, In, Se and then conversion to CIGS by rapid thermal processing (RTP) in a sulfur or selenium atmosphere is another method [3]. Evaporation of CdTe and CdS compounds is also employed.

Development Continues

The short-range disorder and large defect density associated with polycrystalline films and introduced by deposition processes, compared with single-crystal bulk materials, set limits on available short circuit current and therefore on efficiency. Continuing development in deposition processes and materials can improve performance by reducing recombination sites through the growth of a microstructure with longer range order. The focus directed by, for example projects sponsored by SAI, will decrease our dependence on non-renewable energy resources.

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CMN Editor Elected to SVC Board


David Sanchez

We would like to congratulate our colleague, David Sanchez, for his recent election to the Board of Directors of the Society of Vacuum Coaters. David continues a long standing relationship between CERAC, Williams and the SVC, lasting over 20 years. David will bring his unique materials science and PVD experience to a distinguished board of peers and colleagues. His work recently with our Solar and Alternative Energy customers should bring fresh perspectives to Cleantech and other areas of board involvement.

Congratulations David!

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