The Evolution of Photo-Voltaic Solar Cell Technology

Advances in Materials and Processes

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Materion Coating Materials News

In the early 1990s, the technology used for photo-voltaic space solar cells diverged from the silicon technology used for terrestrial panels. Instead, the spacecraft application shifted to gallium arsenide-based III-V semiconductor material compositions. These in turn evolved to the modern III-V multijunction photovoltaic cell used on spacecraft with architectures built of four or more junctions. Silicon solar cells begin life as single crystal silicon with implanted p- and n junctions that generate current when illuminated with light of greater energy than the bandgap of the material.

Physics of a Photo-Voltaic Cell

The physics of photo-voltaic (P-V) cells is based on the generation of current by the separation of mobile charges, electrons and holes, in semiconductor materials. A generic silicon cell is depicted in *Figure 1*. Doping with a small percentage of the appropriate material creates either an excess or a deficiency of electrons (hole), depending on the particular dopant atoms. When the two doped materials are joined, a P-N junction is formed. An electric field develops across the P-N junction by the diffusion of electrons and holes in opposite directions. When the energy of the light incident on a semiconductor P-N junction exceeds the energy with which the outer electrons in the valence band are bound, electrons-hole pairs are created and mobilized by the electric field. In silicon, that energy, known as the bandgap, corresponds to wavelengths shorter than ~1000 nm. Electrons diffuse to the N-type layer, and holes to the P-type layer. The mobile charges are collected by the top and bottom electrodes, and the external circuit returns the electrons and holes to be recombined, thus generating an external current that produces power.

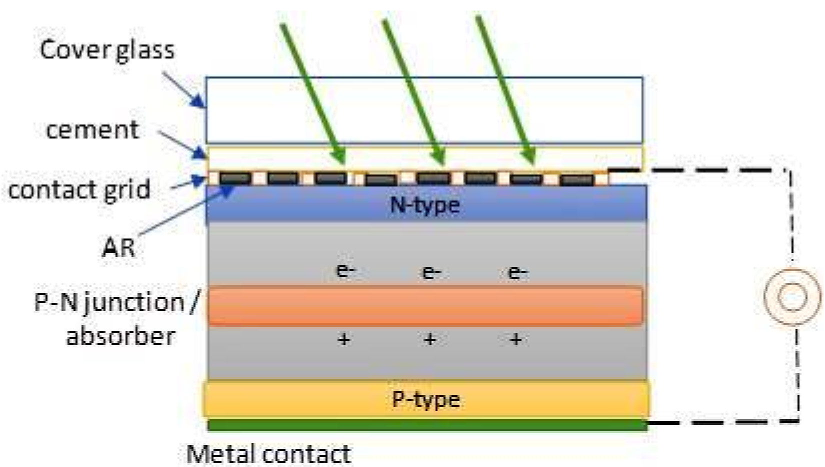

Figure 1. Generic Silicon solar cell construction illustrating the separation of charges at the P-N junction.

The upper electrode is a fine gold wire grid produced by photolithography or by screen printing silver that is then fired. Contact is made to the grid, and to construct a panel many cells are joined in parallel and serial sets to produce the desired panel voltage and current (power). The small loss imposed by the metal grid is tolerated in the interest of economy for terrestrial cells. Developments are underway to replace it by a transparent conductor layer such as indium-tin-oxide (ITO) and other transparent conducting oxides (TCO) for higher performance cells such as those used in space power. The metal electrode at the bottom is often a reflective deposition that returns some photons for a second pass.

Practical Implementation of the Physics Model

The practical physics of P-V cells is a bit more complicated than this simple model implies. Semi-conductor material properties and process issues team to inhibit the full current-generating capability. Defects in the bulk material and surface encourage recombination outside of the electrical circuit, thus reducing the current available for output power. Morphologies other than single crystal tend to have more internal recombination sites. Surface chemical conditions also affects recombination. Passivation layers are often required to minimize surface shunting.

The high refractive indices of semiconductor surfaces produce a loss of photons by reflection values between 30% and 20%, depending on the top layer semiconductor composition. Reflection loss is responsible for the reduction of external quantum efficiency. Increased power output is achieved with an anti-reflection (AR) surface. A layer of Si_3N_4 grown reactively on the silicon serves as an AR and passivation coating. It is as effective as an AR over a limited spectral range. The traditional AR coating for silicon cells is a two-layer TiO_2 / Al_2O_3 design. Coverage is adequate for silicon cells responding to ~1000 nm, but not for the wider spectral band response of multi-junction designs. The AR design required for efficient transmission over ~350 nm to ~1800 nm has three or more layers using Ta_2O_5 and SiO_2. *Figure 2* shows the modeled reflectances of typical AR designs for silicon. Reflectance is within the cemented cover glass. A residual average reflectance of 5% to 7% is present between ~400 nm and 900 nm. Dispersion in the index of silicon causes the reflectance to increase with a wavelength below 400 nm.

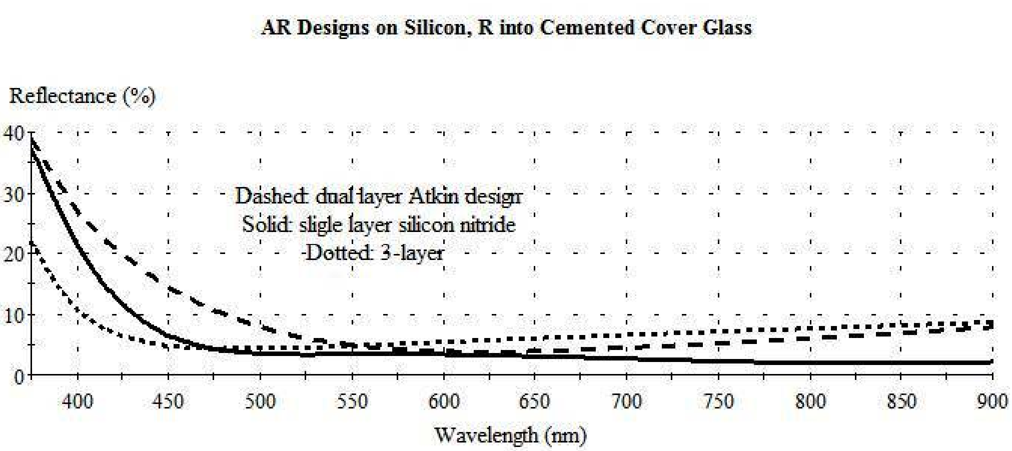

Figure 2. AR performances on a Silicon surface. Minimum values are 3-4%, and bandwidth varies with design.

Little solar radiation reaches the surface of the earth at wavelengths shorter than ~320 nm, therefore, the bandgaps of the semiconductor materials for terrestrial cells were tailored to generate current over wavelengths within ~350 nm to ~900 nm and longer. At the bottom of the atmosphere, wavelengths below 300 nm have been absorbed by the ozone layer thereby protecting life from UV-C (ultra violet in the "C" band) energy. Water vapor and CO_2 have absorption bands in the infrared (IR), as seen in *Figure 3.* The total solar irradiance at the earth's surface is 1.36 kW/m^2 and is composed mostly of visible and near-IR energy with the peak near 450 nm. *Figure 3* shows the spectral insolation for AM 1.5, which corresponds to a zenith angle of 48º. Solar cell current generation is primarily dependent on direct solar irradiation. Extraterrestrial solar emission present above the absorbing and scattering atmosphere, and therefore absent of gas absorption bands, is called AM0 (air mass zero). Sunlight scattered by the atmosphere adds to the total and shifts the effective color temperature to shorter wavelengths.

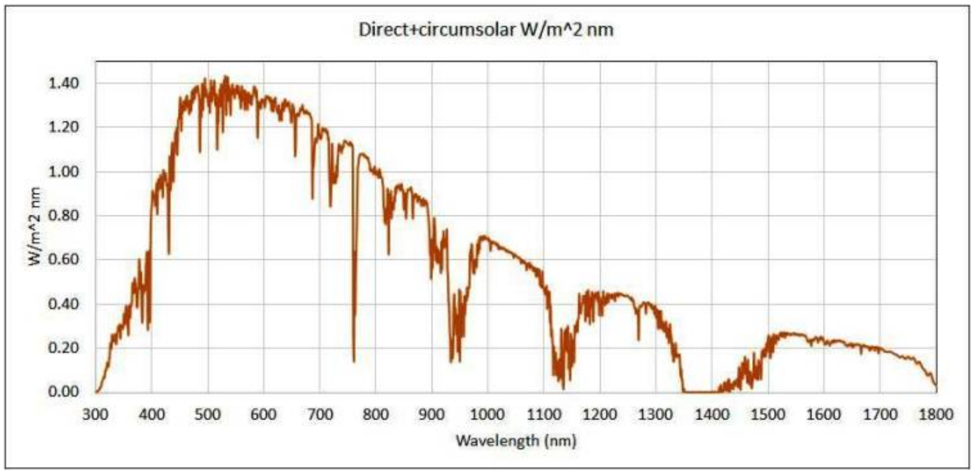

Figure 3. Spectral insolation for AM 1.5. Integrated total is 1.36 kW/m^2. (ASTM G173-03 reference spectrum). Multi-junction cells respond to the energy between ~350 nm and ~1600 nm.

Materials and Deposition Processes

The materials presently used for terrestrial photovoltaics include silicon morphologies as single-crystal wafers, poly-crystal, and amorphous (grown from silane SiH4). An alternate production process to the wafer-based technology is the deposition and growth of Si, CdTe and CIGS in thin-film form on glass, plastics, or stainless steel shim. Deposition processes such as metal organic chemical vapor deposition (MOCVD) are employed for thin-film compositions such as CdTe. Cadmium telluride and copper indium gallium selenide sulfide (CIGS) compositions comprise the second-generation, and multi-junction III-V semiconductors occupy the third-generation category. Thin-film growth technology provides cost savings in raw material consumption, weight, and production facility at the expense of lower efficiency, since the film layers tend to be amorphous. CdTe cells offer higher efficiency and low cost due to their thin-film construction from vapor deposition. However, Cd is toxic and Te is an expensive rare earth element. CdTe technology has achieved the highest production level of all the thin film technologies. Also, it has an energy payback time of eight months, the shortest time among all existing PV technologies.

Cell conversion responses are tailored for maximum current generation from the energy distributed between the near-UV and near-IR. Roughly 90% of PV panels are fabricated from single- or poly-crystalline silicon wafers. Conversion efficiencies at the module level are approaching 20% for single-crystal, but are lower for the poly-crystalline and amorphous forms. Hybrid semi-conductor compositions are created by stacking layers of controlled composition. An example is the dual-junction cell.

CIGS cells with comparable efficiencies are produced from solution, but include indium, an element in short supply. For CIGS cells, the current efficiencies are ~20%. However, the economics of production are not as favorable as for the other technologies.

Third-generation cell architecture builds multiple layers of materials with staggered bandgaps to permit the most efficient conversion of the solar spectrum to electrical power. These special cells are very expensive to produce and are generally applied to space-based power generation systems.

The Nation Renewable Energy Lab (NREL) monitors and tests cell efficiencies and publishes the record breakers [www.nrel.gov/solar]. Cell efficiency for the conversion of photons to electronic carriers depends on the exposed area (determined by the obscuring contact area), the AR coating, cell temperature, and irradiance level. The standard total solar insolation value used for comparisons is 1 kW/m^2. Typical conversion efficiencies for mono-crystal Si are ~19%, for poly-crystalline Si ~12%, for thin-film Si 6-10%, and for CIGS ~20%. Residential flat panel efficiencies are in the range 10 -15% as produced in volume. Therefore, a flat panel array of area 1 m^2 could generate 100 -150 W of electrical power.

Techniques such as coating with a fluorescing dye (dye sensitizing) or texturing the surface to reduce reflection loss have been introduced to increase conversion efficiency. Efficiencies increase with the increase in the concentration of irradiance using focusing optics. An efficiency might be doubled when concentrated to increase the solar power per area from 1 sun to >100 suns. Competing effects are the high temperatures generated in the concentrated beam that will lower efficiency unless a thermal sink is designed into the module.

Manufacturers have designed cells specifically for concentration. Thin-film 3-junction semiconductor cells composed of InGaP / InGaAs / Ge layers have efficiencies as high as 38.5% at 400 suns; 3-J architectures such as $GaInP_2$ / GaAs / Ge produce 30% efficiency at 200 – 400 suns. Further concentration has increased the efficiency for a 4J cell to a record of ~46%.

A promising new material being researched is perovskite (a calcium titanium oxide mineral). This P-V material can be made in thin-film form and easily adapted to large areas such as the sides of buildings.

The push to increase the contribution of renewable energy sources to the total energy budgets of countries around the world has led to competition to lower the price of solar panel installations. Numerous cell configurations, compositions and fabrication techniques are being offered to the commercial market. The price goal of <$1 / Watt is within reach. Worldwide, solar generation accounts for ~2% of electrical power and that figure is growing. Currently, Germany leads the world in producing ~8% of its electrical power by solar farms. [https://en.wikipedia.org***/wiki/***Solar_power_by_country]**.**

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