Photovoltaic materials innovations continue to drive up efficiencies, drive down costs

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ABSTRACT

Materials innovation in solar photovoltaic manufacturing has long played a key role in efforts to raise cell and module conversion efficiencies, improve overall device performance and reliability, and lower the overall cost per manufactured watt. Research and development in areas such as ultrathin-silicon wafering and replacement films for thin-film PV transparent conductive oxides often garner much of the industry's attention. But a wide range of emerging technologies could provide crystalline-silicon and thin-film cell and module manufacturers the kinds of materials solutions that will accelerate their attempts to reach competitive levelized cost of energy metrics and ultimately attain their goal of achieving grid parity with conventional energy sources – as well as open up lucrative market opportunities for the materials suppliers.

Safely moving beyond silane

Few materials in PV manufacturing are consumed as copiously as silane, both in c-Si cell production and, in ever-increasing amounts, amorphous-silicon TFPV fabrication. But the hazardous gas explodes on contact with oxygen, and so it must be transported, stored, and handled onsite with high standards of safety in mind, adding layers of cost and complexity. Throw in volatile pricing and less-than-secure supply-chain scenarios, and silane looks ripe for a replacement solution.

One company, SiXtron Advanced Materials, has come up with a possible alternative for one of solar manufacturing's workhorse substances: a nonpyrophoric, nonreactive silicon-carbon-nitride-based family of gases, available as a solid polymer source, which is showing efficiencies similar to those attained using the conventional silane approach to nitride deposition for antireflective coatings (ARCs). It can also be distributed and supplied to the existing PECVD tools without significant changes in the process flow or equipment configuration.

"We are not generating an unknown gas, we are generating a mix of different gases, but each specific gas in our mix is very well known in the semiconductor industry. People understand that it is not a blackbox," explains Zbignew Barwicz, President/CEO of the venture-backed Montreal-based company. "Because we are depositing a material which is pretty well known, people understand that if we can overcome the tradeoffs and keep only the advantages, this can be huge. We have demonstrated to some extent that we've overcome the different disadvantages of the carbon content, and we keep the advantages from a mechanical and chemical resistance perspective. What is lacking is our understanding of how it behaves on the

Figure 1. SixTron Advanced Materials' SunBox provides a gas generation system for the company's solid-source SiCN used for silane-free nitride deposition.

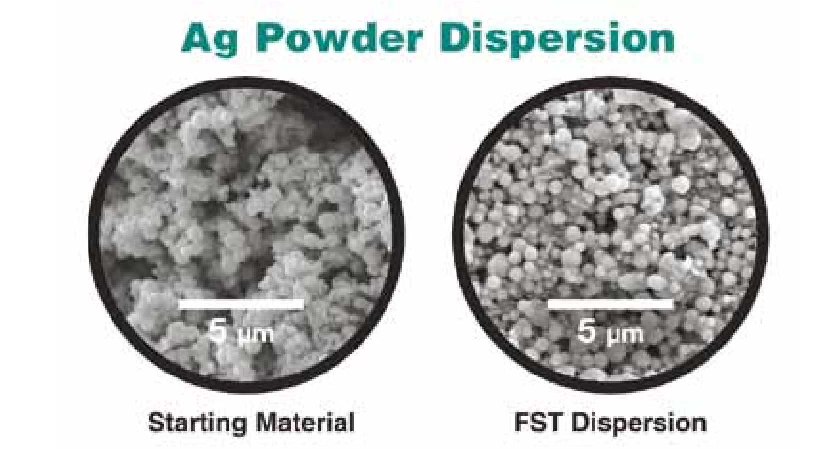

Figure 2. Five Star's silver powder material, before and after dispersion of the particles, shows excellent dispersion uniformity.

cell and how it behaves on the module, and what we are doing now is demonstrating it on the cell and on the module."

SiXtron has been working with Georgia Tech's University Center of Excellence for Photovoltaics (UCEP) to find out just how well the SiCN ARC cocktail behaves on high-performance monocrystalline solar cells, in terms of its optical and electrical properties and ultimately its conversion efficiencies compared to those achieved with conventional silane-based films.

"The beauty of the concept that SiXtron has, is that it generates gases that have carbon in it, instead of SiH_4," said Ajeet Rohatgi, Director of UCEP. "When you flow these gases which are bimetal or trimetal silanes into the same reactor and then flow your ammonia, which you do in the case of silane, the reaction takes place and you still form a silicon-nitride film, but these films have a little carbon in them. They are not 100% silicon nitride, but carbon can be changed by changing the deposition or the composition of the polymer. You can change the composition of the nitride film, and there is an advantage that you can grow films with the same composition using the SiXtron concept in addition to coming up with films that are nonpyrophoric.

"We've been looking at the cells or cell performance with these films and comparing them with the films grown with silane gas," Rohatgi continues. "We have been optimizing the performance and bringing it closer to the conditions of nitride films grown by silane. It took us almost a year of research but now we have produced cells with efficiencies in excess of 17% with the polymer source from SiXtron.

Figure 3. A high-quality printed/fired wafer fabricated using Five Star's ElectroSperse silver front-side contact solar ink.

These efficiencies are very comparable to the efficiencies we obtain with silane-type nitride films. The film properties look quite comparable to silane in terms of measured hydrogen content, transparency, refractive index, and the like."

SiXtron's SunBox gas-source system plays a critical role in the technology's ability to 'plug and play' to the existing PECVD production gear. The box, which contains a cartridge of solid-source polymer and performs as what Barwicz calls a "microplant of the gas" in close proximity to the deposition tools, replaces the conventional – and expensive – gas handling and safety systems used with silane.

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"When we hooked it up to our machine, we removed the silane gas inlet and brought in the SunBox," explains UCEP Assistant Director Abasifreke Ebong, in describing the centre's experience with the system. "Same reactor, we just changed the inlet source, with no modification to the equipment. When we plugged in and used the old recipe, it didn't work, but we were able to work out the recipe and get the same performance (as silane) on the monocrystalline."

In search of ever-finer, sturdier contact lines

Another company benefitting from a relationship with UCEP is Cleveland-based Five Star Technologies, which uses a proprietary hydrodynamic cavitation process to produce silver front-side contact inks and aluminium back-surface field pastes for silicon solar cells. Because of the ElectroSperse S-series materials' tight particle-size distributions and excellent dispersion uniformity, cells can be screen-printed with very fine (well under 100µm) contact lines and achieve consistent electrical contact to the emitter layers (both conventional and high resistance), as well as increase line conductivity, thus improving overall device performance metrics, such as fill factor and conversion efficiency.

Tim Fahey, Five Star's VP of business development, said that the inks and pastes are in commercial qualification trials with 15 to 20 cell manufacturers and turnkey-line integrators in Asia, the United States and Europe, with more to come. The potential customers are intrigued by the data from UCEP, which show that monocrystalline cells printed with the company's silver front-side inks can reach efficiencies in the 17.7-17.8% range, fill factors of 77-78%, and open-circuit voltage (V_{oc}) of >620mV, with very low series resistance (<1) and excellent shunt resistance results.

Unlike conventional pastes, ElectroSperse materials have an inherent adaptability to the wide range of different rapid thermal processor (RTP) firing profiles and process windows in use at solar-cell fabs. With the help of UCEP, Five Star has come up with "a very detailed document we provide to customers with processing guidelines for firing the S-series paste," said Fahey.

"For any front-side contact paste, there's a unique spike temperature that you need to reach," he continued, "in order to get the proper melding of the glass, so the glass can carry the silver down through the antireflective coating to make contact with the emitter layer. Everyone has their own proprietary formulation of what kind of glass they use, so for each paste you need to get to that proper temperature. It's critical to adjust the temperatures to hit the right spike for that particular paste."

UCEP's Ebong explained that researchers have "used the paste, optimized it, based on our understanding of RTP firing with a furnace that we have here. We were able to optimize and get the right firing temperature for them. This is very important because the emitter and the firing profile have to be right in order to obtain the right parameters. Their performance is on par with product pastes."

The next phase of the Five Star/UCEP collaboration focuses on the use of new ink formulations for aerosol, inkjet, and other noncontact methods for printing lines in the tens of microns on ultrathin wafers, what Fahey calls a "natural sweetspot for our technology" because of its particle size and rheology control properties.

Reflect fewer photons, get more energy

While technologies such as SiXtron's silane-free films and Five Star's advanced front-side inks provide enhancements of the solar cell's antireflective properties, another company's approach uses the outer surface of a PV module as the canvas for its innovative AR coating. Xerocoat's durable single-layer optical material, which can be deposited directly on cover glass or even plastic, can increase the transmission of light across the spectrum and at all angles to the cells inside. The ~100nm-thick porous silicon-oxide coating can elevate the watt-peak performance – and thus the energy output – of the module by at least 3% (equivalent to a 0.5-0.75% increase in cell efficiency) and produce about a 4% surge in power on a kilowatt-hour basis, potentially benefiting both module manufacturers and solar PV system owner/operators.

Figure 4. A rendering of Xerocoat's turnkey antireflective coating equipment for PV module production lines.

"From our point of view, we're basically agnostic as to how you convert the photons into electrons. What we do best is getting the most photons we can from the sun on the outside to whatever your technology is on the inside," quipped CTO Michael Harvey. The Xerocoat technology was developed a few years ago at the University of Queensland in Australia by cofounders Harvey and Paul Meredith, who is also VP of materials development of the company, now based in Redwood City, CA.

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Xerocoat's initial market foray involves the 'drop-in' deployment of low-cost, high-volume turnkey coating-and-curing toolsets at crystalline-silicon module makers' production facilities, "which will take glass in from one side, from any manufacturer, apply the ARC to the glass and deliver it to the other side, to the module factory," said Harvey. The newly designed system (which will be made under license by a contract equipment manufacturer) consists of a high-speed, nonvacuum roll-coater, which initially deposits the liquid film on the glass, followed by a relatively simple, low-energy curing step – all done in atmosphere and at room temperature.

"The next big step for us is to complete our pilot line [in Redwood City], which will be using the technologies we have developed for a full-scale production line," said Harvey. "That will be the final step to confirm and demonstrate all the individual technologies we will put together to make a 100MW line. It will have the same throughput and speed of a production line, but we won't be feeding in a half-million pieces of glass per year. It will be completed early in the second quarter. From there, the next step is to ramp up engagement with customers who want to look at the technology in action, see real process tools, and work toward delivering our first coating line in the third or fourth quarter of this year."

Glass coated with Xerocoat's films and laminated onto modules has been undergoing rigorous indoor testing, according to Harvey. Flash testing has confirmed the ARC's merits, while other reliability and durability exams – methods he described as "well beyond the IEC tests" – have revealed no failures.

"As for outdoor testing in Australia, Florida, California, and Arizona," he continued, "what we see is that the coating performs under real-world conditions exactly as we expected under laboratory conditions. The benefits are maintained; in side-by-side comparisons with uncoated glass, the coated glass does not soil at an increased rate, there isn't any evidence that any moderate amount of rain or even dew, dust, and dirt settled on the glass, and it cleaned off more easily on the coated pieces compared to the uncoated pieces. The 3% benefit going out was maintained in the field compared to uncoated glass."

Capturing a slice of real money

Mark Thirsk, managing partner of Linx Consulting and veteran electronics materials market observer, believes Xerocoat's coating approach is a "really interesting piece of technology" that could tap into a growing solar PV antireflective material sector already worth hundreds of millions of dollars. While not citing SiXtron by name, he sees great potential for "deposition systems and materials that replace silane," believing that there is "money to be made" in such efforts. Among the companies innovating in the solar paste and ink realm, he thinks that "Five Star is the most exciting out there," noting how the company's technology "is eminently scalable and potentially brings key advantages." There are "about a half-billion dollars in pastes sold at the moment," he adds, so "if you capture a slice of that, that's real money."