Designing new materials for photovoltaics: Opportunities for lowering cost and increasing performance through advanced material innovations

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Executive Summary

In the last decade and longer, photovoltaic module manufacturers have experienced a rapidly growing market along with a dramatic decrease in module prices. Such cost pressures have resulted in a drive to develop and implement new module designs, which either increase performance and/or lifetime of the modules or decrease the cost to produce them. Many of these innovations include the use of new and novel materials in place of more conventional materials or designs. As a result, modules are being produced and sold without a long-term understanding about the performance and reliability of these new materials. This presents a technology risk for the industry.

This report provides a global survey from IEA PVPS member countries of efforts being made to design new materials for photovoltaic cell and module applications. The report is organized by module component and includes reviews of material innovations being made in: (1) frontsheets, (2) encapsulants, (3) backsheets, (4) cell metallization, and (5) cell interconnects. Section 1 is an introduction. Section 2 presents the state of the art in PV module materials including the functional requirements of each component and the common materials typically used to meet these requirements. Section 3 discusses the motivations for applying new material solutions to PV modules. Section 4 presents the global survey of novel material solutions being developed and tested for the next generation of PV modules.

There are several motivations for investigating new materials for PV modules. Reducing or replacing expensive materials is important for the overall economics of module production. For example, reducing the use of or replacing silver with copper or aluminum leads to a significant cost reduction for manufacturers. Another example is using thinner glass for top sheets or converting from more expensive PVF to less expensive PVDF materials for backsheets. Accelerating the manufacturing process is another way to decrease production costs. Lamination is typically the slowest step in a module production line and manufacturers are very interested in materials that can speed up this process step. For example, fast or ultra-fast cure EVA encapsulants have reduced the time needed for crosslinking from 25 min to 10 min today. Converting to thermoplastic encapsulants, which do not crosslink, may help reduce these times even further. Increasing performance is an obvious motivation for material innovations. This can be achieved with increasing the number of busbars, increasing the active area by using shingling, or increasing light absorption using antireflective coatings, or increasing internal reflections with highly reflective backsheets or white templates between cells. The trend to increasing wafer size also leads to performance gains. Making modules more sustainable is another strong motivating factor. Life Cycle Assessment (LCA) is a methodology to quantify the environmental impact of a product. Some manufacturers seek recognition of ecologically responsible material choices by using various labeling standards to identify good sustainability practices.

A survey of the PV manufacturing industry today shows that there are clear trends in material improvements. Crystalline silicon wafer sizes are projected to continue to increase over time as silicon production improves and results in larger monocrystals that can reach 300 mm in diameter. Cell sizes are expected to increase up to 210 x 210 mm² (M12) in the next several years. New cell interconnection methods are moving to production lines. Manufacturers are instead trying lead-free solder based on bismuth, ECAs, or smart-wire technology. Back contact cells (IBC, MWT, etc.) allow the use of conductive backsheets to interconnect cells. This approach has the advantage of minimizing cell warpage and stress on interconnects due to fact that busbars do not need to cross from the back to the front of the cells, which results in a much flatter package design.
Less developed ideas for module improvement include modules designed for specific climates (e.g. desert, tropical, arctic, high wind or snow loads) or environments (i.e., floating, agriculture). Modules for building integrated applications typically value aesthetic properties as much as or more than energy production. For roof-mounted PV modules, weight can be a limiting factor for deployments. Concepts for making lightweight modules using ultrathin glass and glass-fibre reinforced composite structures or support lattices are being investigated. Vehicle integrated PV requires curved modules, which likely will require materials innovations.
The process of material innovation for PV is further complicated by the complex interactions within a PV module. The advantage of one material may be outweighed by its interaction with another component. For example, EVA is inexpensive and highly effective for encapsulation, however it degrades to form acetic acid which can cause corrosion of the metallization if it is not allowed to escape the module package due to use of an impermeable backsheet. New materials must work within the whole module package and in concert with the other materials present. Consumers and manufacturers rely on international standards, such as those from Technical Committee “Solar Photovoltaic Energy Systems” TC 82 to ensure that new materials do not result in unexpected performance or reliability problems. Another issue is that module manufacturers do not typically advertise their bill of materials (BOM) and the BOM for a particular module model can vary depending on when and where it was made. There exist several nondestructive methods to characterize and identify module materials including FTIR, NIR and Raman spectroscopy.

Frontsheets: PV module frontsheets provide transparency for incoming light, structural protection of the solar cells, electrical insulation and a barrier for moisture and oxygen ingress. While low iron float glass is the most common material used in PV modules, it is heavy, requires tempering for safety, and sometimes presents adhesion problems that can lead to delamination. Frontsheets also typically include antireflective and antisoiling coatings.
Innovations discussed in the area of frontsheets include the use of thinner glass, flexible polymeric materials, and abrasion resistant coatings. Innovations in ultra-thin glass include (1) very low iron contents (100 ppm) that reduces optical absorption, (2) advances in surface texturing, (3) thicknesses between 1.6 mm and 3.2 mm, (4) use of clean room coating step and (5) advances in tempering to reduce built in stresses. The aim is to increase transmission and bending strength while using less material. Fifteen varieties of polymeric frontsheet materials are compared for cost and UV durability. ETFE and PVDF materials have the highest cost while PET based materials have medium to low costs in comparison. Loss in transmission following UV exposure shows a large variability depending on the material. Antireflective and antisoiling coatings can increase performance but there is concern about the durability of these coatings over time. Results of abrasion testing done on various coatings is presented.

Encapsulants: Polymers are used to encapsulate the interconnected strings of PV cells and metal busbars between the frontsheet material and the backsheet. The functional requirements of this component include protection of the cells and metallization from moisture and other environmental contaminates, provide and maintain electrical insulation, and provide adhesion and support between the layered components of the modules. The encapsulant material in front of the cell typically differs slightly in composition from that used on the back side of the cells. The front layer typically is transparent to UV in order to increase light absorption by the cells and UV absorbing in the back layer to protect the backsheet from aging. Ethylene vinyl acetate (EVA) is the most widely used material in PV modules but there is a concern about using this material in glass-glass modules, where diffusion rates are low, since EVA can generate acetic acid as the result of a photolytic degradation reaction. Recently various

polyolefin (PO) elastomers and thermoplastic elastomers (POE and TPO, respectively) are being used for PV modules, especially glass-glass designs. Other materials such as ionomers, poly-vinyl butyral (PVB) and silicones are also being considered and used sometimes.
Innovations discussed in the area of encapsulants include the increasing use of POE and TPO materials instead of EVA. The results of accelerated aging tests comparing TPO, POE and EVA samples show mixed results with some studies reporting TPO and POE samples performing better than EVA and others not. It may be that performance differences may depend as much on the additives added to the bulk material (e.g. UV absorbers) than the specific material used. Recent innovations have resulted in the production of silicone encapsulants in the form of sheets designed to be laminated using conventional equipment. Silicone has been used as a PV encapsulant for especially high reliability applications, but the material has typically had to be applied as a liquid resulting in high costs. Silicone encapsulated modules can survive DH6000 without any signs of corrosion unlike EVA modules cannot.
Cells and cell interconnects: Commercial PV cells come in a variety of different types including Si-wafer based technologies (c-Si), thin films (e.g., CdTe, amorphous silicon, and copper indium gallium selenide (CIGS). Currently most PV modules are made from c-Si cells (e.g., Al-BSF, PERC, IBC, HIT, PERT, etc.). C-Si cells are interconnected in series to raise voltage and lower resistive losses. Conventional interconnection involves connecting metal ribbons or wires to the cells using solder bonds or electrically conductive adhesives (ECA).

Innovations discussed in the area of **cell interconnects** include multiwire and low temperature solders, electrically conductive adhesives and advances in cell metallization. The current trend in c-Si PV cell interconnection is to increase the number of busbars while reducing their width in order to reduce the amount of silver for the cell metallization and increase the module efficiency. This has led to cells with front metallization schemes without busbars, referred as busbarless cells interconnected by means of multi wires. Electrical connection is made during lamination, which avoids the high temperatures required for soldering. This technology has reduced silver usage in modules by as much as 40% compared with a standard 4BB soldered ribbon design. Multiwire interconnection results in less cell cracking, less shading, greater internal reflections and more interconnection points resulting in better performance of modules with cracked cells. Electrically conductive adhesives are composite materials based on a conductive filler and an insulating polymeric adhesive. They are being considered for use in place of solder (e.g., ribbon-based interconnection) for new designs (e.g., shingled) and for attaching conductive backsheets to PV cells. Research is being made on the thermomechanical properties and performance of ECAs in modules. Early results suggest that the use of ECAs can reduce the stress on PV cells compared with soldering. However, there is a wide variety in formulations of available ECAs and differences in performance may partially reflect these differences. Researchers in the US are working to develop a new metal paste formulation designed to be less susceptible to power loss from cell cracks. They have shown that by adding carbon nanotubes to the silver paste used for cell metallization, they can create cells that continue to function normally even when cracked. They have shown that the carbon nanotubes can bridge crack widths up to 70 µm. In addition, even when the cracks resulted in loss of electrical continuity, they were shown to “heal” as thermal and mechanical stresses lessened.

Backsheets: Backsheet materials serve to protect the cells and metallization from moisture and environmental contaminants such as dirt, salt, acids, etc. They also must provide electrical insulation and sometimes even mechanical stability. Multilayered polymeric films are a popular choice as PV backsheet materials. But recently with the market growth in bifacial PV, glass is also becoming a popular backsheet material. Polymer backsheets come in a variety of different materials including polyvinyl fluoride (PVF), polyethylene terephthalate (PET), low density polyethylene (LDPE), polyvinylidene fluoride (PVDF), polyamide (PA) and polypropylene (PP). Backsheet manufacturers also layer different materials and supply commercial names such as TPT (Tedlar-PET from DuPont).
Innovations discussed in the area of backsheets include development of co-extruded backsheets and transparent backsheets. Co-extrusion has better thickness control, reduced processing steps, and allows expensive fluoropolymers (PVF, PVDF) to be replaced by less costly polymers (PET, PA, PP, PE derivatives). Early examples of co-extruded backsheets were made of layers of PA and experienced cracking failures in the field. More recently, co-extruded backsheets made of PE, PO, and PP have been developed. It is too early for extensive field results, but early accelerated tests are promising.

Transparent backsheets made of PVF have been available from DuPont for over 20 years and used in BIPV applications. More recently a new formulation has been developed that is designed to be resistant to UV damage and last for over 20 years. One of the main applications of this would be for bifacial modules in order to reduce the weight and other process complexities of glass-glass modules. In addition, development of transparent backsheets should further advance the development of polymeric frontsheets since both require UV durability.

Lightweight modules: A typical PV module weighs about 12 kg/m². Making modules lighter makes sense as it would decrease shipping and installation costs and open up new application spaces such as large buildings with limits on the load bearing capacity of their roofs. There are several examples of certified lightweight and flexible thin film solar modules with weights as low as 2 kg/m² that need to be bonded directly to a flat roof. Research is also being done to design standalone lightweight modules using a glass-backsheet designs along with a light-weight lattice and beam structure. Early prototypes have achieved 8 kg/m².

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