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Flexible CIGS modules – selected aspects for achieving long-term reliable products

Markus Münch, **Annegret Reithe**, **Melina Wachsmuth**, **Michael Meißner** & **Eva-Maria Stahr**, Solarion AG, Leipzig, & **Mike Röllig**, Fraunhofer Institute for Non-destructive Testing (IZFP-D), Dresden, Germany

ABSTRACT

Flexible copper-indium-gallium-(di)selenide (CIGS) absorbers offer a wide range of possible applications in rigid as well as flexible and lightweight solar module designs. The main advantage of CIGS in comparison to the well-known flexible module technology based on amorphous silicon is its currently higher efficiency and the promising optimization potential of its efficiency in the future. Because of low cell thicknesses of less than 40µm and the general sensitivity of CIGS to moisture, it is a challenge to develop suitable interconnection and encapsulation technologies that promote long-term reliability of solar modules. Selected aspects of our work in this area will be discussed in this paper.

Introduction

Solarion manufactures flexible copper-indium-gallium-(di)selenide (CIGS) solar cells on highly flexible polymer substrates in a proprietary low-temperature ion-beam-assisted deposition (IBAD) process. The core technology was developed in 1996 at the Leibniz Institute for Surface Modification in Leipzig, and Solarion was founded in 2000 as a spin-off company. Focus was placed thereafter on the development of the process and equipment for roll-to-roll (R2R) manufacturing. Today Solarion operates an R2R solar cell pilot line and a solar module pilot line, as well as a module test facility. A mass production line with a nominal annual capacity of 20MW is currently under construction.

Figure 1. A highly flexible CIGS solar cell from Solarion.

The solar cells are manufactured on an ultra-thin polymer substrate employing the IBAD manufacturing process, which deposits a thin layer of CIGS on the lightest substrate available at a reduced deposition temperature of about 400°C. The cell materials are deposited in a continuous R2R process, and a thin, silver-based contact grid is printed on top of the cell. This is converted to a batch of single cells, each having an area of 56cm^2, which are then sorted into several power classes in a similar way to that used for crystalline solar cells (Fig. 1). A sophisticated marking and tracking system ensures the traceability of all materials and process parameters from the raw materials of the cells to the completed module.

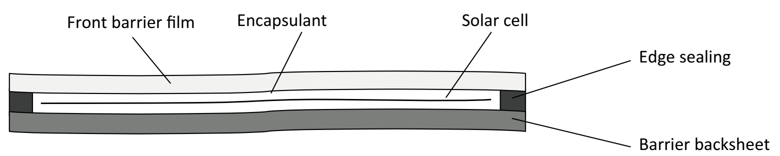

Figure 2. Typical cross section of a flexible CIGS solar module.

> "Because of low cell thicknesses of less than 40µm and the general sensitivity of CIGS to moisture, it is a challenge to develop suitable interconnection and encapsulation technologies that promote long-term reliability of solar modules."

A cross section of a glass-free CIGS solar module is illustrated in Fig. 2. Because of the moisture sensitivity of CIGS, in order for an environmentally stable, hermetically-sealed module to perform reliably for more than 20 years in the field, it is necessary to apply the following materials: transparent barrier film, cell encapsulant, edge sealing and barrier-containing backsheet material. The interconnection between the flexible solar cells inside the module is realized using polymer-based conductive adhesives. These materials are well established in flexible electronics and were included in the investigations.

Owing to their light weight and flexibility, Solarion's CIGS cells lend themselves well to a wide range of possible designs and applications, such as building-integrated photovoltaic (BIPV) and automotive projects, among others.

Module R&D activities

Besides its solar cell R&D, Solarion has undertaken intensive solar module research, focusing on product and technology development as well as reliability and safety testing, with the latter being a widely underestimated concept in PV technology [1]. The majority of the common standard module tests and module materials tests are performed in-house at the module reliability laboratory. Advanced reliability and safety tests are conducted by partners.

A flexible encapsulation technology was developed for Solarion's cell technology after a wide variety of polymeric materials were investigated. The optimal materials and their system compatibility, particularly with the solar cell, were identified by intensive research and testing over the past four years of 25 conductive adhesives, about 20 barrier films, 20 different encapsulants, 6 types of edge sealing and several backsheets.

Methods of investigation

Several methods were employed for determining usable materials and their combinations in order to achieve the development target. IEC 61646 is the baseline standard for the definition of accelerated ageing tests of solar modules. While damp-heat testing at 85°C and 85% relative humidity accelerates hydrolysis and material decomposition as well as interactions in or between polymers, it also allows the investigation of moisture ingression into a solar module package. Temperature cycling between –40°C and +85°C induces thermomechanical stress, mainly due to different coefficients of thermal expansion (CTE) of the module materials.

UV exposure is merely defined as a precondition test in IEC 61646. Given the glass-free, polymer-based composition of flexible modules, UV exposure must be given a greater level of importance by a longer test duration. Combined humidity and UV tests in accordance with ISO EN 4892-3 were therefore undertaken, using increased UV intensity to study the synergistic effect of moisture and UV radiation exposure. The samples were additionally exposed to humidity–freeze cycles at temperature extremes of –40°C and +85°C. All the tests were terminated when a power below 90% of the original rating was observed, or when the samples would fail a visual inspection. Postmortem studies were performed, as required by the IEC norm, in order to identify the degradation mechanism. Typical failure mechanisms of, but not limited to, crystalline solar modules in accelerated ageing are described by Wohlgemuth [2].

Accelerated mechanical ageing of the flexible modules was performed using a cyclic bending test over a roll diameter of 300mm in order to simulate the typical stress imparted by coiling up for shipment and uncoiling for installation. In addition, vibration tests using an electromagnetic

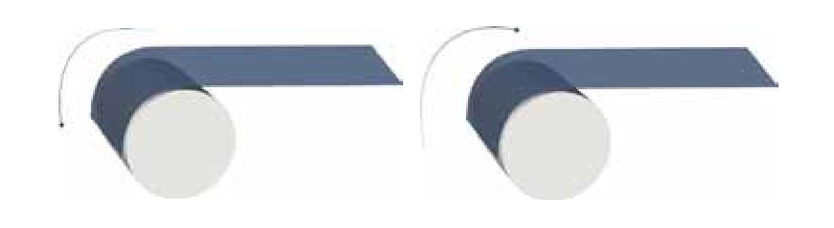

Figure 3. Bending (left) and straightening (right) of a flexible solar module.

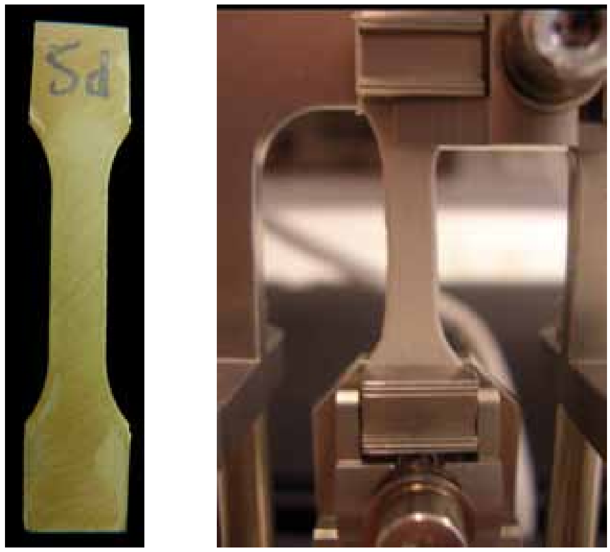

Figure 4. Test specimen made from conductive adhesive (left), and in the testing position (right) for linear DMA.

Figure 5. Effects of moisture ingress due to adhesion loss: delamination (left), and degradation as indicated by an electroluminescence image of a mini-module (right).

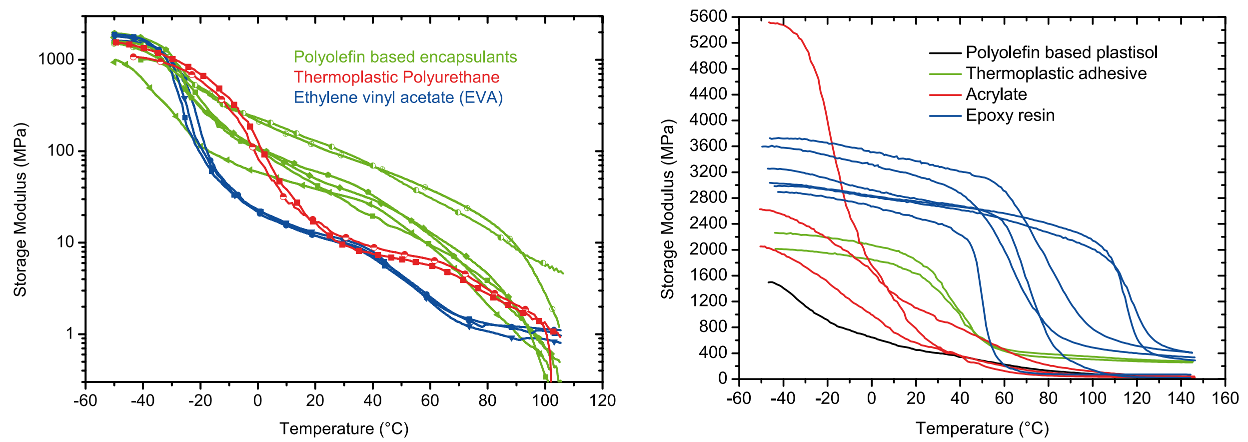

Figure 6. Storage modulus vs. temperature for different encapsulants (left) and polymer conductive adhesives (right).

shaker were carried out to investigate the susceptibility of flexible modules to forced oscillations of up to 200Hz. Frequency and amplitude were measured by a laser vibrometer.

A pulsed AAA sun simulator was used to determine the electrical parameters of the samples, while electroluminescence testing, infrared imaging, laser-beam induced current testing (LBIC), lock-in thermography (LIT) and optical microscopy were used for failure analysis.

A number of material characterization techniques were employed in order to understand the materials' properties and their respective interactions at the module level. The method of choice was dynamic mechanical analysis (DMA) for investigating the thermomechanical behaviour of polymers for encapsulants, barrier films, edge sealings, and polymer-based interconnection materials. The aim was to investigate the elasticity of materials over the typical operating temperature range of solar modules from –40°C to +85°C. As opposed to the procedure used in Kempe [3], linear DMA was conducted for system-adapted test specimens in order to ascertain their respective storage moduli over a range of temperatures (Fig. 4). Adhesion testing between laminated films, encapsulants and edge sealings was performed according to ISO1139:2010 (Adhesives – T-peel Test for Flexible-to-Flexible Bonded Assemblies). Additional mechanical tests, for example a fracture test before and after weathering, were performed to investigate microstructural processes in the polymers. As a further analysis, the dimensional stability of encapsulants with residual stresses was tested under high temperature in accordance with the following procedure – samples of encapsulant were cut to a dimension of 50mm × 50mm, powdered with talcum and placed onto a heating plate at 105°C for 10 minutes.

Key factors for reliable flexible CIGS module encapsulation

The following key factors can be identified by experimentation.

Adhesion and chemical compatibility

Adhesion and chemical compatibility of neighbouring materials are the most important requirements in achieving long-term stable products. The goal is to have neighbouring materials form a sufficiently strong adhesive bond so that cohesive fracture is exhibited during a peel test, not just after lamination but also after accelerated ageing. Inadequate adhesive bonding typically leads to delamination and loss of moisture-barrier protection in module packaging.

During and after the ageing procedures, interactions between materials could be observed: for example loss of adhesion at the interface, outgassing, material decomposition, loss of structural strength and discoloration. Most of these effects could be observed after damp-heat testing or combined UV and damp-heat testing. Consequently, the impact on the module of elevated temperature, moisture and UV radiation may lead to failure mechanisms and subsequent module failure in the field. It is easy to see that stringent testing of materials and their compatibility is vital to the subsequent approval of their use in flexible solar modules.

Thermomechanical behaviour

The thermomechanical behaviour of polymeric materials used as encapsulants and conductive adhesives was characterized by DMA. In this procedure, viscoelastic properties can be gleaned from glass transition and time-dependent deformation behaviour of materials over a significant temperature range from –40°C to above 100°C. A wide variety of storage moduli were observed (Fig. 6). Some of the conductive adhesive materials lose their flexibility at low temperatures and fail under stress. Furthermore, encapsulants are susceptible to creep at high temperatures due to softening.

Encapsulations based on polyolefin (PO), polyurethane (TPU) and ethylene vinyl acetate (EVA) were simultaneously characterized. Distinctive glass transitions at around –20°C were observed for

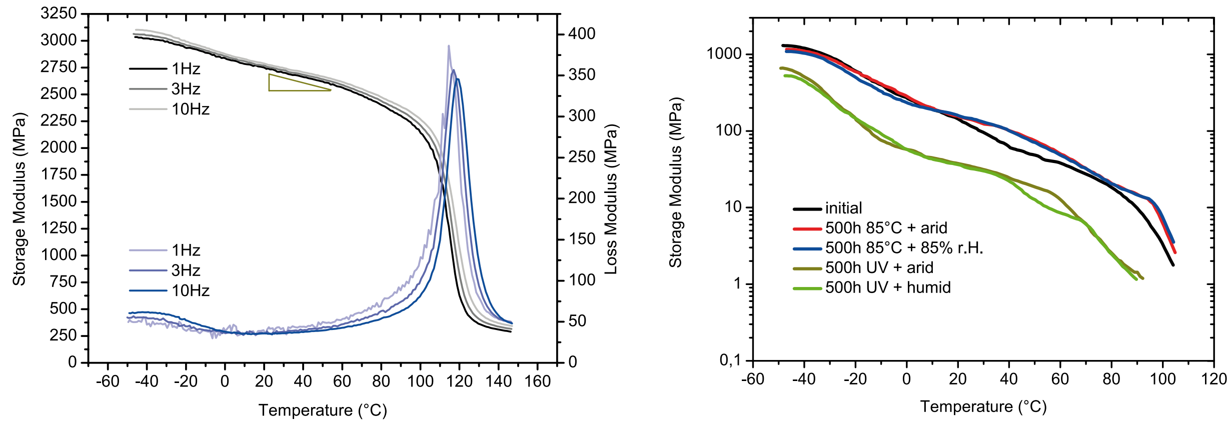

Figure 7. Left: storage and loss modulus vs. temperature of an epoxy-based conductive adhesive with characteristic glass transitions and phase changes. Right: storage modulus vs. temperature of a thermoplastic encapsulant for different environmental influences.

Figure 8. Dimensional changes of different encapsulants before (far left specimen) and after shrinkage tests. Two EVAs and four thermoplastic materials were investigated.

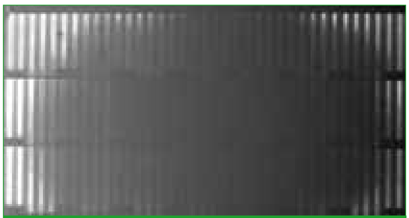

Figure 9. Electroluminescence image of a mini-module showing degradation caused by moisture ingress through the front barrier film.

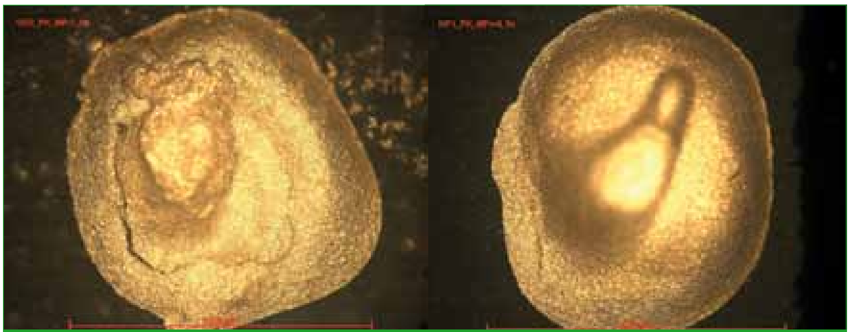

Figure 10. Results of the vibration test. Left: with high-modulus conductive adhesive, mechanical stress has caused the interconnection dot to fracture. Right: with modified conductive adhesive, the interconnection dot is stable.

EVA materials: this represents the thermodynamic phase transition from a crystalline to an amorphous microstructure. The extreme change in material stiffness at very low temperatures leads to high stresses inside an assembled module, and this greatly increases the risk of overloading the encapsulation–neighbour interface. At high temperatures, some EVAs exhibit irreversible material transport that leads to a significant reduction in stiffness. For a long, stable module lifetime, material transport within the module at elevated temperatures and overstressing at low temperatures must naturally be avoided.

Environmental influences

A study was made of the effects on module performance of environmental conditions such as

- Moisture (85% relative humidity at 85°C)
- UV light under dry conditions
- UV light under wet conditions
- Temperature storage (85°C)

The material characterization was then repeated (Fig. 7).

The time-dependent material

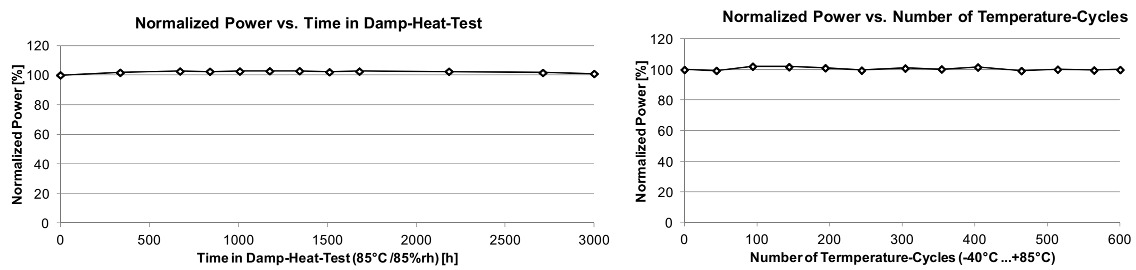

Figure 11. Stability of flexible CIGS modules in temperature-cycle and damp-heat testing.

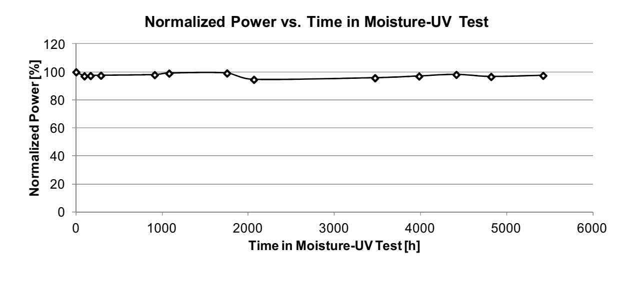

Figure 12. Stability of flexible CIGS modules in combined moisture and UV testing.

deformation and glass transition within the operating temperature range are also critical to the use of polymeric materials in flexible modules. The choice was made to use materials that exhibited linear elastic behaviour over the specified operating temperature and showed no significant modulus changes around the glass transition point. Locally high stresses due to material deformation must be prevented.

Dimensional changes

Besides the specified physical properties of materials, the parameters of the manufacturing process can significantly influence the processability and service life of the module package. For example, volumetric dimensional changes due to residual stresses (Fig. 8) can lead to displacement of the solar cells and ribbons, and can bring about additional mechanical stresses inside the layer composition. In extreme cases, the destruction of the solar cells and/or interconnection structures could be observed.

> “The test modules in the combined moisture and UV testing have been verified to exhibit long-term stability with practically no power degradation.”

Water vapour transmission

Low water-vapour transmission of the materials investigated and very strong resistance to moisture in field applications are additional key factors in flexible CIGS module reliability. These properties are ensured by the transparent front barrier film, the backsheet material and the edge sealing that prevents water vapour ingress via the module edges [4]. CIGS solar cells are known to be sensitive to moisture, and so it was necessary to evaluate a variety of barrier materials with water vapour transmission rates less than 10^{-3}g/m^2. Otherwise, there could be a large variation of moisture sensitivity, depending on the individual production processes of the different CIGS manufacturers and the materials that they use [5]. Moisture ingress into the module and the resulting cell corrosion can be deduced through the use of electroluminescence imaging (Fig. 9).

Mechanical stress

External mechanical stress can also influence the long-term stability of solar modules. Whereas typical crystalline and thin-film glass modules are rigid and thus susceptible to brittle fracture, flexible solar module materials and their respective interfaces must be able to withstand bending and oscillation forces imparted during production, shipment, installation and operation. Beyond the load tests of IEC 61646, additional cyclic bending tests were applied to flexible modules to ensure their high quality and durability over the guaranteed lifetime. The modules were stressed over a 300mm-diameter drum in convex and concave geometries, and in lengthwise and transverse cell directions. When the preferred interconnection and encapsulation technologies were used, no change in power of the modules was evident after 2000 bending cycles.

Further investigations were conducted with vibration tests that showed significant differences in the fatigue behaviour of the cell's interconnection materials. Brittle fracture was observed on high-modulus materials, whereas flexible conductive adhesives exhibited superior stability. The use of modified and matched materials for interconnection and encapsulation leads to excellent vibration stability of the complete system.

"For a long, stable module lifetime, material transport within the module at elevated temperatures and overstressing at low temperatures must naturally be avoided."

Conclusion

Understanding relevant properties of materials and their concomitant interactions is vitally important for developing a general understanding of flexible module packaging. This knowledge allows the development of robust solar modules that could potentially perform far beyond the requirements of IEC 61646, which typically reveals only early failures. The investigations presented in this paper thus define pre-qualification procedures in order to select suitable materials and their combinations in the short term, without the wasted effort of building complete modules in the early phase of product development. Only materials exhibiting positive test results can be brought to process and product qualification. This reduces the risk of premature test failures and avoids significant iterations with, and extensive parallel testing of, multiple material candidates on the module level.

The module technology that has been developed consists of flexible interconnections and a hermetically-sealed cell package that exhibits excellent long-term reliability. In accordance with IEC 61646, damp-heat tests were performed for three times the required length of time, and the temperature-cycle test for three times the required number of cycles: no test sample showed any significant electrical degradation. Likewise, the test modules in the combined moisture and UV testing have been verified to exhibit long-term stability with practically no power degradation.

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About the Authors

Markus Münch holds a degree in electrical engineering from Leipzig University of Applied Sciences. He has worked in the PV business since 1997, with responsibilities that have included product development and management. Markus joined Solarion in 2008 and is currently the Solar Module Division Director, leading a team responsible for product and technology development as well as module reliability.

Mike Röllig received a diploma in electrical engineering (M.S. in engineering) from Dresden University of Technology, and completed his Ph.D. in material science and engineering in 2008. His work in the field of microsystems technology, packaging and material characterization focuses on the measurement of the material properties of lead-free solders for industrial applications. Mike is currently employed at Fraunhofer IZFP-D as the head of the department of test and diagnosis methods.

Enquiries

Markus Münch
Solarion AG
Ostende 5
04288 Leipzig
Germany
Email: markus.muench@solarion.de

Mike Röllig
Fraunhofer Institute for Non-destructive Testing
Maria-Reiche-Straße 2
01109 Dresden
Germany
Email: mike.roellig@izfp-d.fraunhofer.de