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Encapsulation polymers – a key issue in module reliability

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ABSTRACT

The majority of solar module manufacturers use ethylene-vinyl acetate (EVA) copolymer foils as the encapsulant material for solar cells and thin-film modules. Because EVA needs long processing times for curing, thermoplastic process materials that do not employ chemical cross-linking have been coming more and more into focus in the encapsulation sector. This paper takes a look at the mechanical temperature-dependent properties of a variety of such materials.

Introduction

From a processing point of view the advantage of a thermoplastic polymer without chemical cross linking is that the material just needs to be molten up, flow around the inner module components and cooled down. Thus, a repeated lamination cycle is possible whereby the polymer is again made molten and imperfections could be removed. Depending on the viscosity of the polymer melt, holding and pressing times during vacuum lamination can be reduced significantly.

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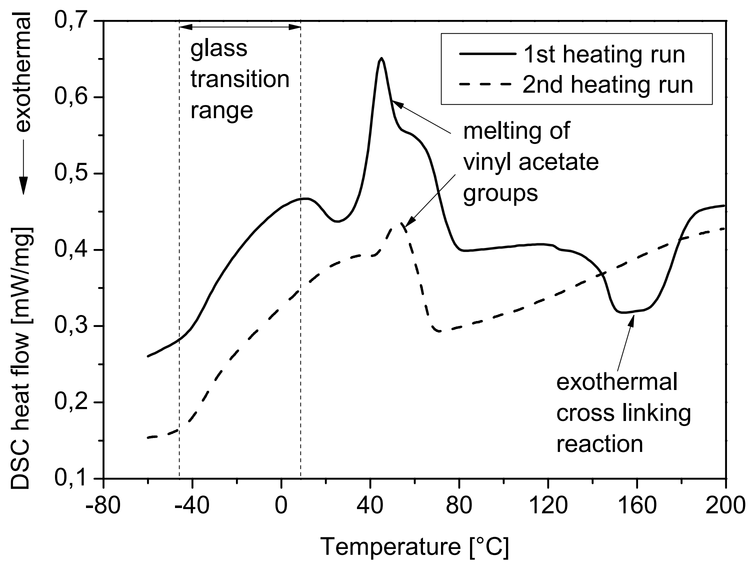

Figure 1. Heat flow diagram of an EVA encapsulant at a heating rate of 10K per minute.

Putting aside the advantages and disadvantages of their specific aging behaviour, different encapsulant materials show a variety of mechanical properties that directly affect the reliability of module components. During operation or certification procedures modules are exposed to constant or cycling mechanical or thermo-mechanical loads resulting in stress in module components, such as glass, solar cells or copper ribbons, as well as interfaces. Polymers show a strong dependancy over temperature in their mechanical properties such as Young’s modulus. Since solar modules can be defined as laminate structures from a mechanical point of view, the shear-taking polymeric interlayer mainly influences the deflection of a solar module under load. Numerical simulation techniques can be applied to estimate the influence of the interlayer properties on the mechanical response of the module and its components.

In combination with adequate characterization techniques such as Dynamic-Mechanical Analysis (DMA), material parameters can be determined easily for a wide temperature range. In this work, the mechanical temperature-dependent properties of Polyvinyl-butyral (PVB) Trosifol Solar R40 (Kuraray), Thermoplastic Silicon Elastomer (TPSE) Tectosil 185 (Wacker Chemie) and EVA Vistasolar 496.10 (Etimex) will be discussed.

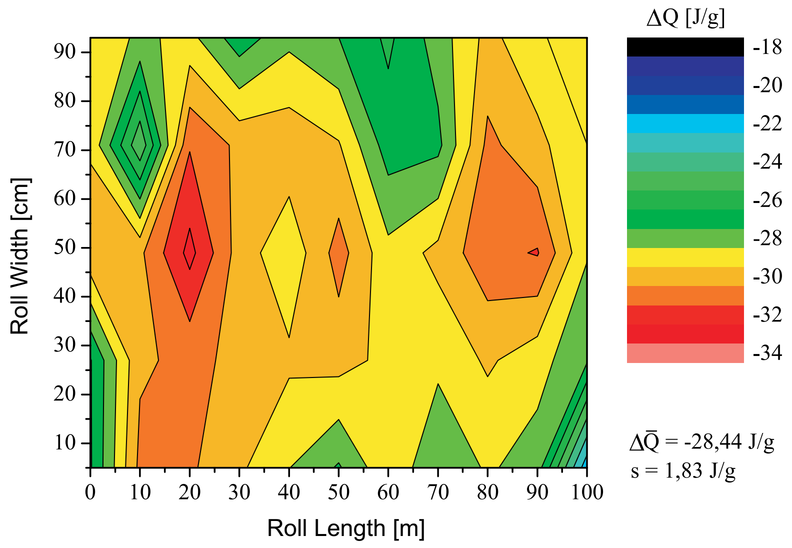

Figure 2. Total heat released during exothermal curing reaction ΔQ for an EVA encapsulant along foil dimensions (standard EVA, no Etimex material).

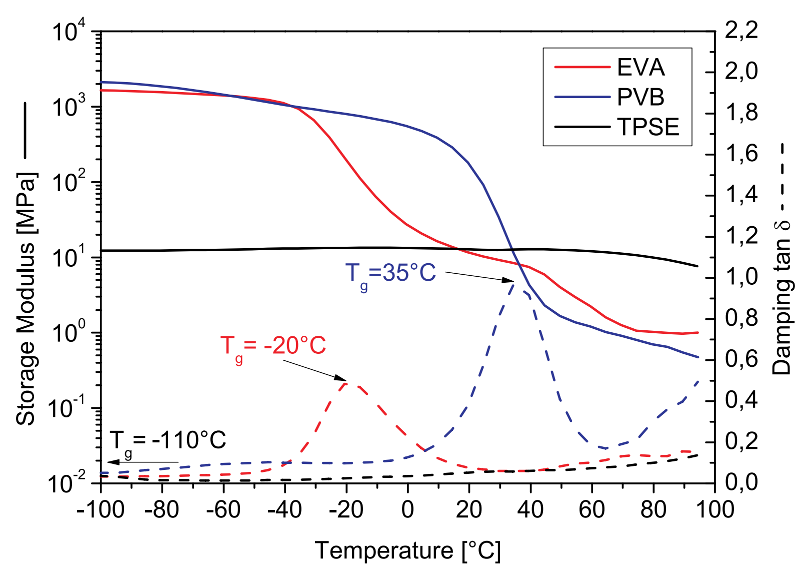

Figure 3. Storage modulus over temperature for different laminated encapsulate foils.

EVA curing at a glance

Differential scanning calorimetry (DSC) can be used to characterize the curing of EVA. This method is well established in polymer science and can give results of the onset of temperature-induced cross-linking. Covalent cross-linking of EVA is achieved by activation of cross-linking agents that are incorporated into the polymer foil and results in a non-meltable elastomeric molecule network. The principal operating mode of DSC is the measurement of heat that is taken or released by the analyzed material during physical or chemical transitions or reactions [1].

A typical heat flow diagram the first and second heating runs for a typical EVA encapsulant is shown in Fig. 1. For the first heating run of the uncured material, the area of glass transition can be found in the temperature range from -40°C to 10°C as a strong change in specific heat capacity. Between 40°C and 80°C, the melting of vinyl acetate groups occurs, followed by the exothermal reaction of the cross-linking. Given that this reaction peak is not present in a second heating run, it is clear that the cross-linking agent becomes totally consumed at the end of the first heating run.

The initial phase of the exothermal reaction can be found at around 120°C as a deviation of the base line. This point represents the minimum temperature required to start a measurable reaction. Additionally, the total heat that is released can be an integral of the heat flow, representing the peak area above 120°C. Taking into account that the total amount of heat which is released during the curing process directly corresponds to the concentration of cross-linking agent in the sample, an estimation of EVA polymer foil quality is possible.

For example, the results of DSC measurements along the length and width of an EVA foil are shown in Fig. 2. It is clear from this schematic that the cross-linking agent does not disperse well in these types of foils. The reason for this is the method in which the additives are incorporated into the melt during foil manufacturing, details of which shall not be discussed here. The degree of cross-linking, which is a function of the amount of cross-linking agent, directly affects polymer properties; therefore, lamination of solar modules can result in locally distributed properties. It was found that the stiffness of the laminated foil, which was determined by tensile testing, did not change after varying holding times during lamination between 5 minutes and 60 minutes. So it can thus be assumed that the distribution of stiffness over the dimensions of an EVA foil can be assumed as statistically homogeneous. The effect of the remaining cross-linking agent – if not totally consumed – on the local chemical aging in solar modules is still uncertain and is a current topic of research and discussion.

Polymer stiffness

One of the most important parameters for characterizing the elastic load-deflection behaviour of solar modules under distributed load is the Young's modulus, or stiffness, of the polymeric interlayer. Several characterization techniques, such as tensile, shear or bending test, can deliver information regarding elastic load-deformation behaviour. One disadvantage of these static tests is that determination of temperature-dependent properties is very time-consuming. In response to this, DMA measurements were carried out in tensile mode using a frequency of 1Hz on rectangular laminated polymer stripes. The temperature was swept between -100°C and 100°C and the glass transition temperature T_g could be determined using the maximum in damping. One resulting parameter of these tests is the storage modulus E' representing the elastic part of the deformation. For low frequencies, this modulus can be equalized with the static modulus E, which is a result of standard tensile-tests and is used as an engineering parameter for calculation of solar module mechanics.

Fig. 3 shows the storage modulus over temperature for all three polymer types tested. A strong temperature-dependence of stiffness was found for PVB and EVA. The glass transition or softening temperature, as the peak maximum in tan δ, was determined at -20°C for EVA and 35°C for PVB. For TPSE, this characteristic temperature is below -100°C and therefore was not detectable during this test. While a rise in temperature results in a significant loss in mechanical properties for PVB and EVA, especially in the region of glass transition, TPSE shows nearly constant mechanical properties over the relevant temperature region of -40°C to 85°C.

Module mechanics under load

From a mechanical point of view, a thin-film module is essentially a laminated piece of glass. The encapsulant acts as an adhesive that establishes a so-called shear bond between the glass panes and therefore the mechanical properties of the

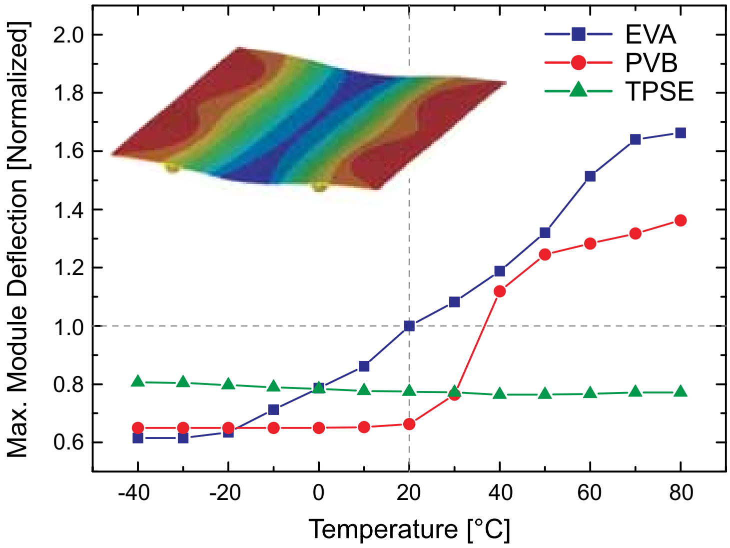

Figure 4. Maximum module deflection for different encapsulants at various temperatures of a common thin-film module with back rail support, normalized for an EVA at 20°C.

Figure 5. Large climate chambers conform to IEC standards at Fraunhofer CSP.

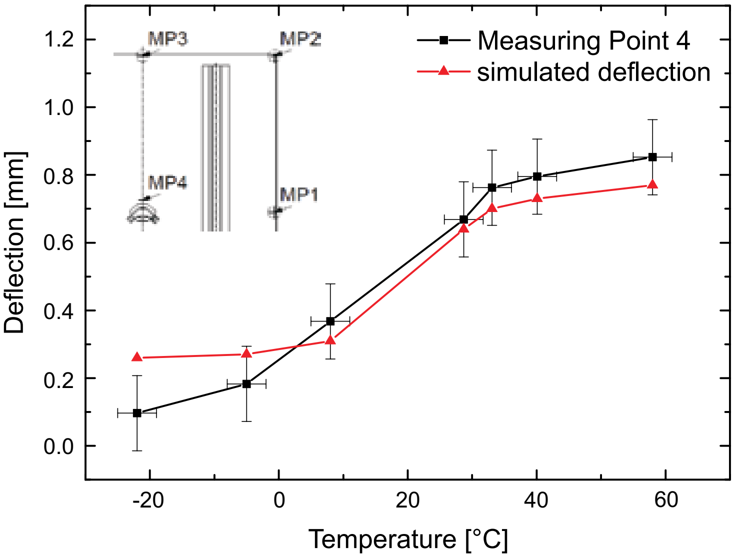

Figure 6. Measured maximum deflection of a thin-film module with PVB encapsulant and back rail support (load: 760Pa).

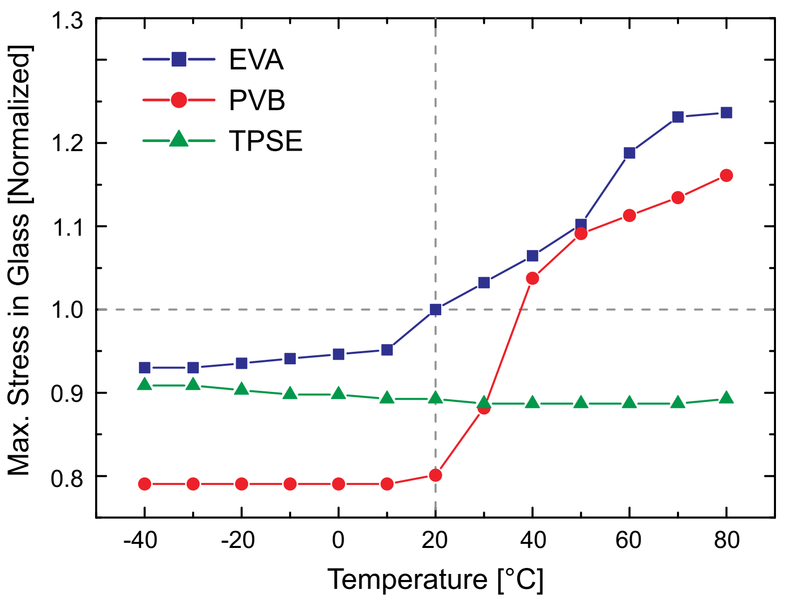

Figure 7. Variation of the normalized maximum tensile stress in glass of a thin-film module with back rail support, normalized for EVA and a temperature of 20°C.

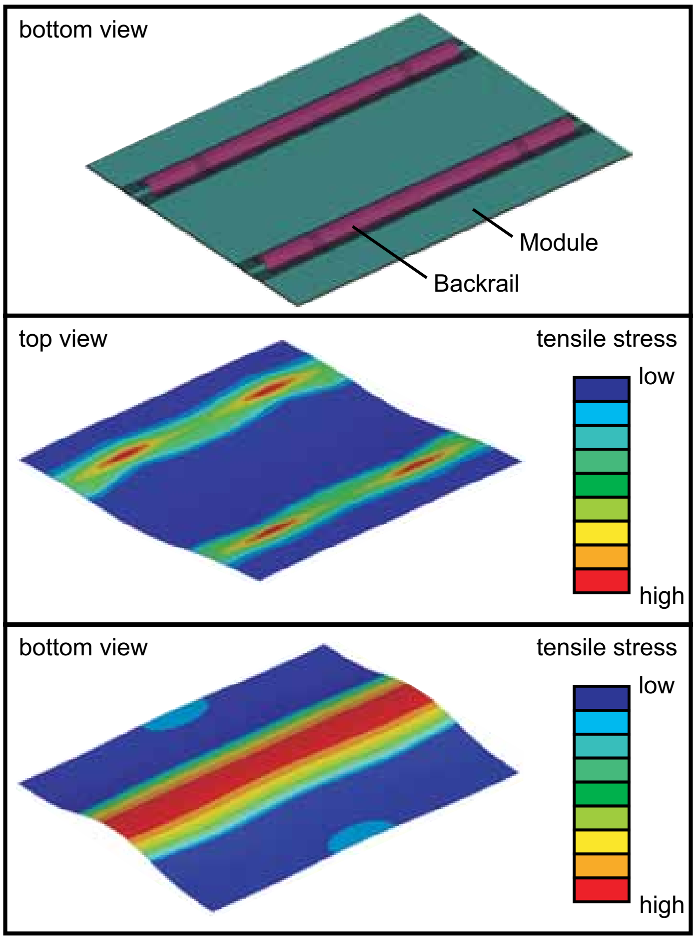

Figure 8. Generic first-principle stress-contour plot of a back rail-supported layered glass module under distributed load.

encapsulant directly affects the behaviour of the mechanical system [2]. In order to mechanically qualify a module, it has to withstand a distributed load of 2.4kPa in compression as well as suction in three cycles for one hour according to the IEC 61646 standard. This represents a wind speed of 130km/h with a factor of three. Higher requirements involve the testing of a snow load of 5.4kPa. These tests are performed at room temperature. A solar module experiences a wide range of temperatures during operation. High temperatures above 80°C are possible under intensive solar radiation [3], while snow actually is present below 0°C. This means that the only attention that is paid to the temperature dependence of the encapsulate stiffness is covered by the security factor.

> "With the help of the finite element method (FEM), the deflection and mechanical stresses in the module can be simulated for different load situations and temperatures."

For this reason, the mechanical system is actually very sensitive in the range of the material properties of the encapsulant. With the help of the finite element method (FEM), the deflection and mechanical stresses in the module can be simulated for different load situations and temperatures. Since the absolute numerical results are dependant on various parameters such as module size and mounting, the following results are normalized to room temperature values of EVA for a standard 3D-FE-model developed at Fraunhofer CSP.

Fig. 4 shows the normalized maximum deflection of a thin-film module (2.2 × 2.6m) with back rail support for different interlayer materials. At low temperatures, most polymers show high stiffness values, resulting in a small maximum deflection of the module.

On the other hand, the low stiffness at elevated temperatures leads to an increased deformation, since it is easier for the glass panes to act against each other and cause higher interlayer shearing. Comparing PVB and EVA with TPSE interlayer modules, the deflection stays nearly constant for the whole temperature range, which corresponds to the results in Fig. 3.

A special experiment was performed with a view to verifying these results. This approach involved the mechanical load testing of a thin-film module in a climate chamber (Fig. 5). The measured deflection for the measurement point in the centre of the module along with the corresponding simulated deflection is in Fig. 6, showing that the results of the simulation and experiments corresponded well in the temperature range between -20°C and 60°C.

The dependency of module deformation from temperature is an indicator that the stresses in the glass are also affected. This effect can be seen in Fig. 7, which depicts the normalized maximum tensile stress in the glass over temperature. The results of

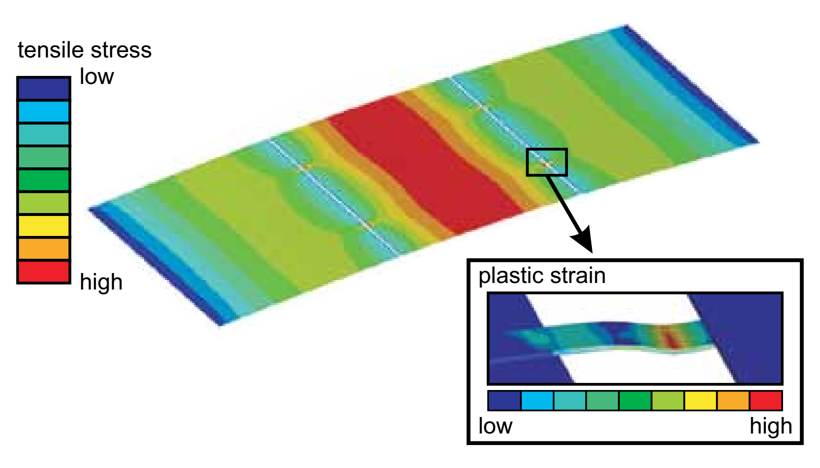

Figure 9. Finite element result of a laminated cell string showing first-principle stress in the silicon. Inset: plastic strain in copper ribbon.

this simulation showed that higher polymer stiffness lowers the stress in the glass, and vice versa. For the analyzed PVB, the glass transition is located at room temperature, which can lead to a wide range of results in the fail/not fail statistics as the temperature interval between 20°C and 60°C results in a glass change of about 31%.

> "TPSE and EVA experience a minor creep deformation due to the physically or chemically cross-linked molecular structure."

Solar-grade EVA shows a broader range of softening but results in similar effects. In this example, the induced stress for an EVA laminate at 60°C is 19% higher than stresses seen at 20°C and -20°C. Stiffer EVA leads to 6% lower stresses. As the stiffness of the TPSE encapsulate is nearly constant over the investigated temperature interval, the maximum stress variation in the glass is relatively low. Fig. 8 illustrates a characteristic stress distribution in the glass for a thin-film module with back rail support under distributed load. In those calculations the back rail support was not allowed to deflect. The highest stresses are located at the end of the back rails on the front side and between the back rails on the bottom side of the module.

Comparing the materials at a standard testing temperature of 20°C, one may assume that the PVB is superior to the other materials in the mechanical load test. This consideration is only valid for short-term behaviour and does not account for the strong time-dependant deformation behaviour of the materials, particularly PVB. The PVB tends to creep intensely above glass transition temperature [3]. In contrast, TPSE and EVA experience a minor creep deformation due to the physically or chemically cross-linked molecular structure.

Mechanical stress in solar cells

An important issue in assessing the long-term reliability of crystalline solar modules in terms of yield is the consideration of the reliability of module components such as copper ribbons and solar cells. Since they are encapsulated into the polymeric matrix, the load, which is applied to those components, is strongly dependant on the mechanical properties of the encapsulant material. Over the past few years, the thickness of solar cells has been decreased rapidly from 300µm to 180µm, while further developments down to 120µm are planned. This, however, increases the tendency of solar cells to form cracks, which in the long term will decrease module efficiency and subsequently yield. Incorporating the specific processing-dependant material properties of the encapsulate polymer and the module structure – including each component and material layer – allows the investigation of loads on solar cells with a mechanical model. These loads are brought about by a range of external conditions such as wind, snow or temperature changes. Recent studies have seen the development of a modelling concept allowing various investigations into the mechanical behaviour of the module systems [4]. The research was focussed on a standard module layout consisting of a front glass sheet, an EVA encapsulant and a polymeric back sheet. In order to gain an understanding of the basic mechanical behaviour, a laminated specimen consisting of a single solar cell string under bending support was investigated under distributed load by finite element analysis. These calculations show that highest mechanical stress occurs in the centre cell (Fig. 9). Moreover, a great deal of attention must be paid to the high strain at the interconnectors, as cyclic loading due to temperature changes, wind or snow loads can result in local hardening and breakage [5,6].

The results of the simulations show that it is important to implement the temperature-dependant mechanical properties of the polymer. As we have shown in [4], the stiffness change of the EVA between -20°C and 40°C and the solar cells themselves have an impact on the module deflection. This effect is comparable to thin-film modules, with the difference that the shear bond partners are now the cell string and the glass. The development of the deflection of the laminate shows a similar behaviour pattern. Incorporating solar cells into a module can lead to a decrease of laminate deflection of more than 20%. Furthermore, the thickness of the solar cells influences the stiffness

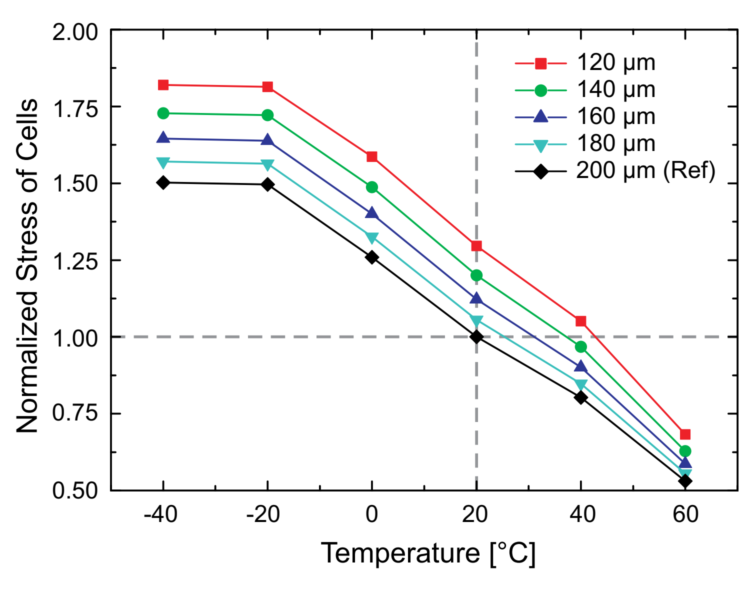

Figure 10. Dependency of the maximum-principle stress in solar cells on temperature and cell thickness, normalized for a cell thickness of 200µm and 20°C [4].

of the laminate. A second study, which focuses on tension stresses in the solar cells, shows an equivalent behaviour over temperature (Fig. 10). At -20°C, the stress in the silicon is increased by 50% compared to room temperature. As the reduction of the thickness of the solar cells lowers laminate stiffness, module deflection increases, leading to higher stresses in the solar cells.

Simple stress-strain diagrams over the cross-section can deliver an insight into this mechanical behaviour. As mentioned, module components like solar cells are coupled by the polymer to the glass front sheet. During mechanical loading, the module glass bends, leading to tension strain at the adverted side of the load. Due to the perfect coupling between polymer and glass, this strain is consequently applied to the polymer/glass interface. Since the stiffness of the encapsulant is usually extremely low, a large amount of this strain can be compensated. Nevertheless, some strain is transferred to the solar cells, setting them under tension load.

Armed with this mechanical understanding, it is obvious that the stiffness of the polymer is crucial to the stress in the solar cells. Reliability studies at room temperature do not apply for other temperatures when using polymers. These materials exhibit a large transition of material properties within the operation temperature range of solar modules that directly influences module mechanics.

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About the Authors

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Sascha Dietrich studied mechanical engineering at the Leipzig University of Applied Sciences and University of Paisley/Scotland. His master's thesis at the Fraunhofer Institute for Mechanics of Materials (IWMH) investigated the reliability of silicon structures. Since 2008, he has been working at Fraunhofer CSP in the field of finite element simulations of photovoltaic modules and components and became head of the Module Reliability team in 2010.

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