The role of encapsulants in standard and novel crystalline silicon module concepts

Verena Steckenreiter, **Arnaud Morlier**, **Marc Köntges**, **Sarah Kajari-Schröder** & **Rolf Brendel**, ISFH, Emmerthal, Germany

ABSTRACT

Encapsulants play a crucial role in ensuring the long-term stability of the power output of PV modules. For many years the most popular encapsulation material for crystalline silicon modules has been ethylene vinyl acetate (EVA), which leads the market because of its cost-effectiveness. Innovations in crystalline silicon cell and module technology, however, have changed the requirements that the encapsulants have to meet. A wide range of other encapsulation materials is also available; such alternatives offer improved outdoor stability and gains in module performance. Furthermore, innovative module concepts that have new sets of requirements are under development. One attractive module concept in particular envisages the attachment of pieces of crystalline Si to the large module glass at an early stage, followed by the processing of the Si cell and the series interconnection at the module level using known processes from thin-film photovoltaics. This so-called thin-film/wafer hybrid silicon (HySi) approach relies heavily on module-level processing of Si solar cells, and is a new field of research. This paper discusses the applicability of silicone encapsulants for module-level processing and compares their requirements with those of conventional EVA.

Introduction

For a PV module to be a cost-efficient source of electricity, its lifetime needs to be as long as possible. Today's module manufacturers grant warranties of up to 30 years. During this time, the solar cells must be shielded from environmental stresses, such as wind and snow loads, humidity, temperature and UV radiation.

The encapsulant plays a crucial role in shielding solar cells from the elements: it is used to fix the cells behind a rigid transparent cover sheet to ensure protection against the outdoor environment, as shown in Fig. 1. The key features of the encapsulation material are:

- Suitable transparency in the solar-cell-relevant spectrum [1]
- Durability against UV light, temperature and humidity [2]
- Adequate mechanical adhesion to the glass, solar cell and metal components
- Low elastic modulus to buffer the solar cells mechanically from the glass [3]
- Electrochemically neutral material to avoid corrosion [3]
- Acceptable handling, processability and process-speed [4]

The stability of the encapsulation material itself is, moreover, of the utmost importance for the long-term stability of PV modules. In the wear-out phase the quality of the encapsulant determines the browning and delaminating speed and hence the service lifetime of the PV module. The delaminating phase is typically the beginning of the end of the service life [5]. Even if the delamination itself does not lead to a significant power loss of the PV module, the peeling process allows water to initiate electrochemical corrosion of the metal parts of the solar cells and interconnection ribbons.

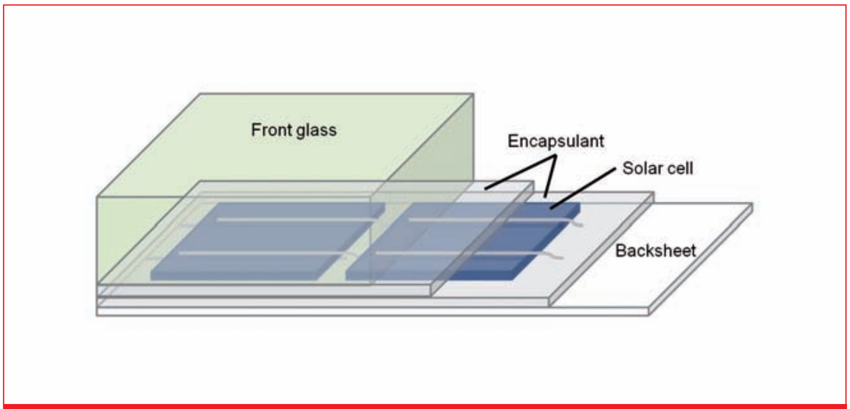

Figure 1. Lay-up schematic of a standard module.

> "The stability of the encapsulation material itself is of the utmost importance for the long-term stability of PV modules."

The first commercial modules used silicone rubber and polyvinyl butyral (PVB) as the encapsulant [6]. Since the early 1990s the most common encapsulation material used in PV modules has been ethylene vinyl acetate (EVA) [6]. Lots of materials have now been developed and are competing with EVA in the PV market, for example thermoplastic polyurethane (TPU), polyvinyl butyral (PVB), polyolefin (PO), ionomer, thermoplastic silicone (TPS) or silicone [7]. All these materials have specific advantages over EVA, but their higher prices have prevented their extensive use in the cost-driven PV market.

Silicon solar cells and PV modules, however, are continuously changing and improving significantly; this leads in some instances to changing encapsulant requirements and may increase the attractiveness of new encapsulants. Additionally, radically novel module concepts could emerge that have a different set of requirements for the encapsulant.

This paper summarizes the properties of the state-of-the-art encapsulant EVA, reviews the changing requirements for encapsulants of standard PV modules, discusses an innovative concept that requires module-level processing of solar cells, and investigates the challenges for the encapsulant in those concepts.

Properties of the standard encapsulant EVA

EVA is obtained by the copolymerization of ethylene and vinyl acetate in various ratios according to the field of application. The bulky vinyl acetate group hinders the crystallization of the material and acts as a plasticizer. Controlling the ratio of vinyl acetate in the copolymer allows the synthesis of materials with tuneable mechanical, chemical and electrical properties [8]: for solar-grade EVA, the typical vinyl acetate weight ratio is about 33% [9]. The use of EVA in PV modules requires a cross-linking step in the material processing, i.e. the irreversible formation of intermolecular covalent bonds between the chains, after which the polymer cannot be made molten but only softened by heating. EVA has a low melting point (60–80°C), and is therefore easily processable before it cross-links. This cross-linking is achieved during the lamination of the modules at temperatures between 140 and 160°C, and requires maintaining the module at these temperatures for 10 to 15 minutes, since the cross-linking reaction is not instantaneous. This step is still one of the most time-consuming steps in module production. EVA compounds destined for the solar industry contain initiators, such as peroxides or other radical-forming species, to allow cross-linking of the material. These initiators – as well as other additives, such as adhesion promoters, antioxidants and UV absorbers – are integrated in the polymer matrix during the extrusion of material into foils. The radical-forming initiators are activated by heat during lamination but are also degraded by UV light, or they simply evaporate when the EVA is not properly stored in an opaque sealed foil, resulting in a short shelf life. This has implications on module manufacturers' supply chains.

EVA degrades and discolours under exposure to UV light and is therefore usually protected by a UV stabilizer: this additive absorbs wavelengths under 350nm to protect EVA from harmful radiation, thus also limiting the photon flux reaching the solar cell. Nevertheless, UV absorbers are not sufficient for preventing the degradation of the material. Laboratory exposure of EVA laminates to UV destroys the UV absorber [2,10]: over time this leads not only to an increasing transparency of the material in the wavelength range 300–350nm, but also to a progressive decrease in transparency in the wavelength range 350–650nm, causing a noticeable yellowing of the material [9,11,12]. This yellowing is presumed to be due to the formation of π-conjugated products, which may occur on the polymer backbone itself [9] or on the by-products of degraded additives [12]. Silicone encapsulants [13] do not show absorption in this range, and their UV stability does not require the addition of a UV absorber, thus allowing an optimal transparency in this range. Furthermore, when exposed to UV light, thermoplastic and thermosetting silicone encapsulation materials display a lower decrease in discoloration and transparency than EVA over time [14].

Degradation of the embedding material under UV exposure, or through heat and moisture hydrolysis, leads to the release of acetic acid. The formation of such a product may have a direct impact on module performance stability, since acetic acid may contribute to the corrosion of the contacts and the metallization of the solar cells [15,16].

During the cross-linking process, the radical initiators are consumed, as are the stabilizing agents. Nevertheless, a short lamination time may lead to a large amount of reactive initiators remaining in the module. An ageing study carried out at ISFH on modules encapsulated with EVA with different degrees of cross-linking has shown that the residual peroxides and other cross-linking initiators reduce the weathering stability of EVA [2]. Under UV exposure or under damp-heat conditions, the EVA material containing residual cross-linking initiators has been shown to yellow faster and exhibit a greater amount of fluorescent degradation products than the fully cross-linked EVA, in which these initiators are depleted. Silicones demonstrate a higher stability against UV light and heat load than hydrocarbon polymers, as the intrinsic stability of the covalent bonds in silicone is much higher than that of the covalent bonds in polymers such as EVA or PVB [17].

> "Silicones demonstrate a higher stability against UV light and heat load than hydrocarbon polymers."

Two factors need to be taken into consideration in determining the ideal degree of cross-linking. On the one hand, a low degree of cross-linking leads to a low viscosity of the material, causing an outflow of the material from the module and eventually delamination. On the other hand, achieving a high degree of cross-linking with certain fast-curing materials containing large amounts of cross-linking initiators provokes the formation of bubbles in the laminate [2]. This negative effect of the residual chemically active additives on the stability of the encapsulant is a further argument in favour of thermoplastic materials for standard PV applications, as these will allow higher process flexibility for a manufacturer, without the need to take into consideration the consumption of the remaining cross-linking initiators.

Besides this susceptibility to degradation caused by the additives, pure carbonated polymers display an intrinsic sensitivity to high temperatures. EVA spontaneously degrades in a few minutes at temperatures of about 250°C [18], and a four-hour exposure of additive-free EVA to temperatures of about 180°C leads to a dramatic discoloration of the material.

Change in requirements for encapsulants because of improvements to standard PV modules

Several developments have led to enhanced requirements for encapsulants:

- Improvements to solar cells
- Newly identified degradation mechanisms
- Constraints due to cost-reduction measures

Improvements to solar cells

Today's solar cells have an improved UV response [19]. The UV blocker in an EVA-based encapsulant, however, typically absorbs the UV spectrum up to a wavelength of 360nm (10% transmittance) [20], which means that about 0.25% of the cell current is lost in the EVA [19]. Improving the UV transparency of EVA is therefore important [20]: one possibility is to change the UV blocker in the EVA. If the number of high-energy UV photons in the EVA is increased, however, there is a higher risk of browning and delamination of the encapsulant, because of the UV-driven decomposition of the EVA molecular backbone. Other materials, such as silicone, are stable with respect to UV radiation and therefore do not require UV blockers, which allows the full advantage of the improved UV response of new cells to be realized. However, since these materials are still more expensive than EVA, the benefits of any cell-to-module power gained may be negated by the additional cost of the UV transparent encapsulant.

Newly identified degradation mechanisms

Besides solar-cell-related aspects, newly identified degradation mechanisms of modules demand improved characteristics from the encapsulants. Module manufacturers therefore currently face the challenge of producing solar modules free from potential-induced degradation (PID) [21]. There are many ways to achieve that goal [22,23], one option being to optimize the encapsulant. It is not yet clear what exactly causes the PID sensitivity of the encapsulation material. However, the UV-blocker concentration [24] and the specific bulk resistivity of the encapsulant [25] seem to influence the PID sensitivity of a PV module. A PID-optimized encapsulation material makes the module manufacturer less dependent on the cell manufacturer.

Constraints due to cost-reduction measures

The silicon wafer accounts for 30% of the module cost, so manufacturers try to reduce the thickness of the wafer material to decrease costs [26]. Thinner solar cells raise the requirements for the soldering process and for the mechanical decoupling of the solar cell from the module glass by the encapsulant. EVA materials have a glass transition (i.e. the transition between the brittle, vitreous state and the rubber-like state) above –20°C, and therefore within the temperature range of PV module applications [3]. A lamination material with a low modulus of elasticity and without a glass transition in the range of application may be necessary. From a mechanical point of view, silicone-based materials may therefore be a suitable alternative.

Emerging module concepts – towards module-level processing

As well as the continuous improvements in standard PV modules, the PV research community is currently exploring novel module concepts that offer additional cost-reduction potential. Thin-film/wafer hybrid silicon (HySi) technology [27,28] is a module concept that aims to combine the high efficiency potential of crystalline Si (c-Si) layers with the low cost per area of Si thin-film photovoltaics. This approach is considered to be an innovative option for cost reduction [29].

An integrated series connection for solar cells created from the porous silicon (PSI) layer transfer process [31,32] was demonstrated by Brendel and Auer [30] in 2001. A proof-of-concept mini-module achieved a power conversion efficiency of 10.6%.

Various concepts involving HySi technology are currently under investigation. The integrated-interconnect module (i^2-module) is being developed by imec [33]: the intention is to glue front-side-processed back-contact solar cells to a glass superstrate. This concept can potentially be used for very thin Si foils. A proof-of-concept device with a rear-side processing on a permanently bonded carrier has been demonstrated by imec; this solar cell device yielded a power conversion efficiency of 10.3%.

Another HySi concept is the crystalline silicon interconnected strips (XIS) module from ECN [34]: here, thin cell strips of thickness 3mm are processed into back-contact heterojunction solar cells. ECN currently glues front-side processed wafers to a superstrate; the bonded wafers are then separated into thin strips, which subsequently receive the a-Si:H junction and back-surface field (BSF) formation, metallization and interconnection. The attachment facilitates the handling of many small strips. A proof-of-principle device of 14 series-connected strip cells has demonstrated a V_{oc} of 8.5V [35], but no power conversion efficiency has yet been announced.

A HySi approach in which the rear side of two-side contacted solar cells is processed before bonding to a permanent module substrate has been proposed by ISFH [28]: the silicon wafers are passivated on the rear side and then bonded to an aluminium-coated glass. For this approach, laser pulses fire the aluminium locally through the passivation layer on the rear side of the solar cell to form contacts and provide the mechanical bonds. All subsequent process steps take place at the module level. The

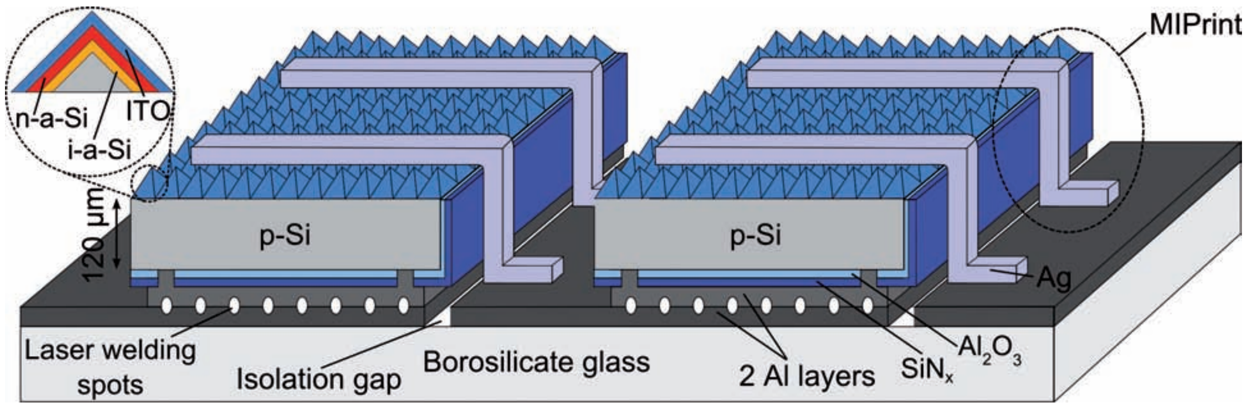

Figure 2. The module interconnection printing (MIPrint) technique for cell interconnection [38]. After the solar cell stripes are bonded to a substrate by laser welding, the screen-printing step is performed at the module level.

bonded wafers are textured and undergo a wet-chemical cleaning; they then receive an i-a-Si:H passivation and an n+ a-Si:H heterojunction. Next, an indium tin oxide is sputtered, and the silver screen printing is carried out. A single solar cell fabricated in this way demonstrates a power conversion efficiency of 19.1% [36,37].

ISFH has also demonstrated the so-called module interconnection printing (MIPrint) method [38]: the module interconnection of a-Si:H heterojunction solar cells of a MIPrint module, shown in Fig. 2, combines cell metallization and interconnection. Fig. 3 illustrates the interconnection of cells using a screen-printed metallization paste. The silver-containing paste is printed over the edge of the solar cells so that the front side of one solar cell connects to the underlying aluminium rear-side contact of the neighbouring solar cell. The designated area conversion efficiency of such a module is 17.0%, and lifetime testing is currently under way.

Many more HySi approaches in addition to those discussed here are conceivable. All HySi technologies apply at least one cell-processing step at the module level, with all the silicon wafers or stripes being attached to the module glass. The more attractive HySi approaches employ the majority of cell-processing steps at the module level. Module-level processing (MLP) imposes additional requirements on the encapsulant, since the encapsulant has to also withstand the processing environment and subsequently outdoor exposure, as well as allowing high cell efficiencies.

Typical MLP steps include, for example, wet-chemical cleaning, texturization, deposition of the passivation and the emitter, and metallization. This means the encapsulant must demonstrate sufficient resistance to the chemicals used during solar cell processing (alkaline texturization, laser-damage etch, wet-chemical cleaning); moreover, it has to be stable during processes that take place at elevated temperatures and low pressures. Potentially suitable encapsulation materials like silicones restrict the process temperature to a range of 200 to 260°C, thus allowing low-temperature processes such as passivation and junction formation by a-Si:H deposition. Apart from these process-related requirements, such encapsulants have to feature the same properties for sufficient long-term stability as those offered by the materials used for standard encapsulation. When used for sunny-side encapsulation, as suggested for some HySi approaches, transparency in the solar-cell-relevant spectrum is also essential.

Encapsulants for module-level processing

Standard encapsulant sheets, such as EVA, are not compatible with module-level processing owing to their thermal instability. Furthermore, thermoplastic materials are not suitable for this specific application because of their remelting characteristics at temperatures below those used in cell processing. Materials such as liquid thermosetting silicones offer possibilities beyond the standard encapsulation of wafer-based solar cells.

Addition-curing two-part silicones demonstrate sufficient stability during UV exposure and humidity–freeze cycling, as well as during chemical and thermal treatment [39]. Consequently, addition-curing two-part silicones are promising candidates for use in module-level processing. The cross-linking of this type of silicone occurs by catalysis through a Pt metal complex and is accelerated by heat [40]. As a result of the additional cross-linking after the mixing of the two components, no by-products are released.

> “Addition-curing two-part silicones are promising candidates for use in module-level processing.”

The most crucial process step of MLP in the presence of silicones is the passivation and junction formation by a-Si:H deposition. The impact of silicones on the passivation layer has been reported in the literature [33]. The annealing of silicone-bonded samples at temperatures in the range 235 to 300°C – analogous to an a-Si:H deposition and beyond – yields a sufficient thermal stability [39]. However, silicones may be affected by a combination of the effects of temperature, vacuum and plasma during the plasma-enhanced chemical vapour deposition (PECVD) of passivation layers.

To verify the quality of the passivation, two lifetime measurement methods are performed on Si samples that are glued to glass with silicones.

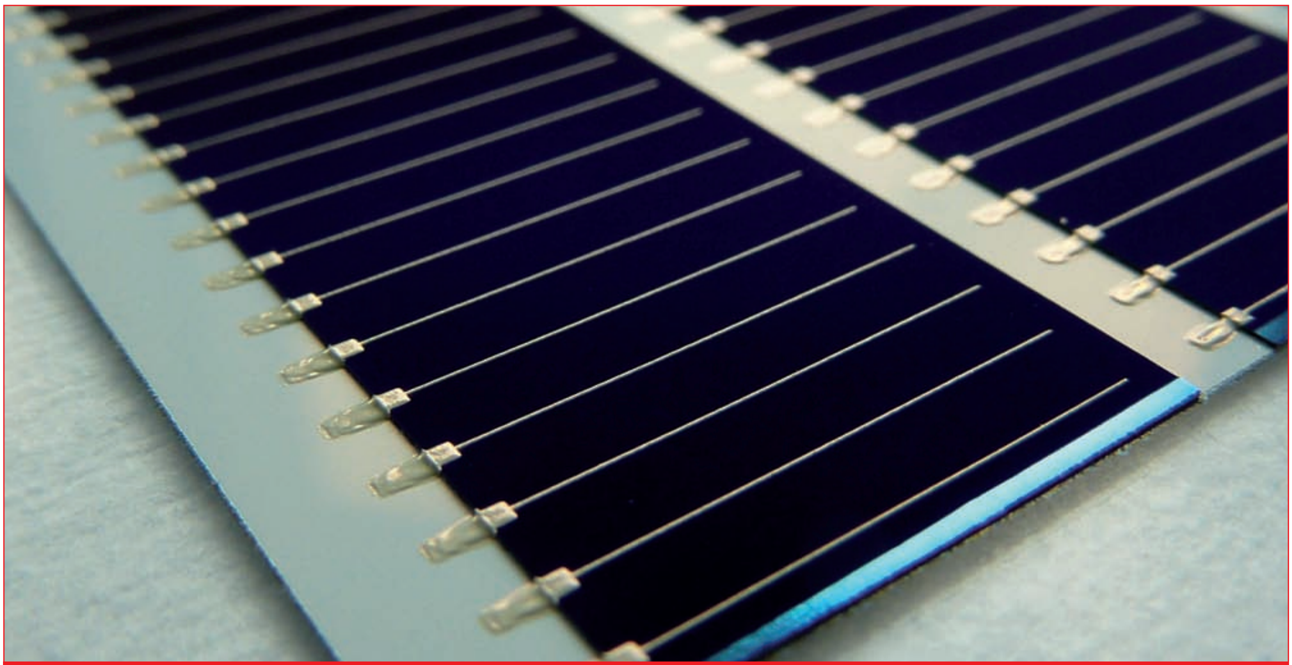

Figure 3. The screen-printed interconnection of cells in the MIPrint module prior to lamination [38].

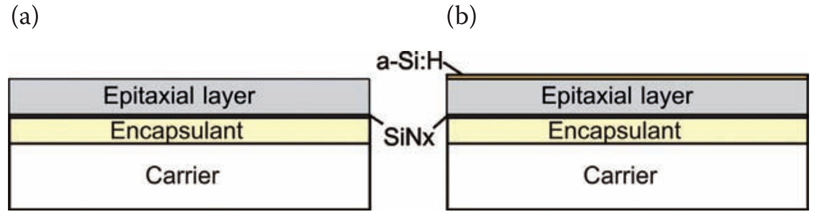

Figure 4. Cross section of a one-side passivated epitaxial layer glued to a carrier: (a) prior to the a-Si:H deposition; (b) after deposition.

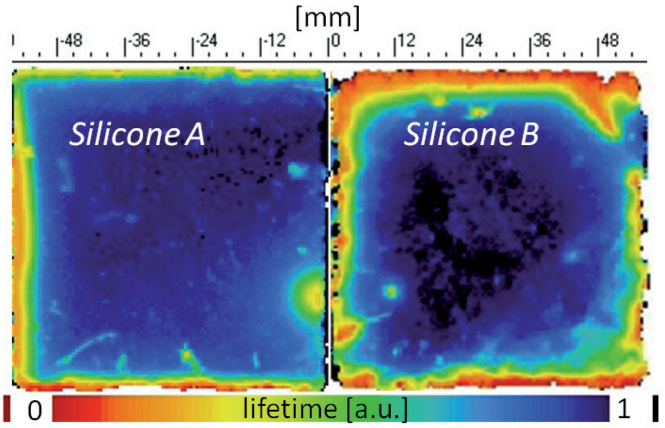

Figure 5. Thin Si layers that have been front-side passivated by SiN_x when still attached to the substrate wafer. After bonding with two-part silicones and detachment, these layers were rear-side passivated by a-Si:H.

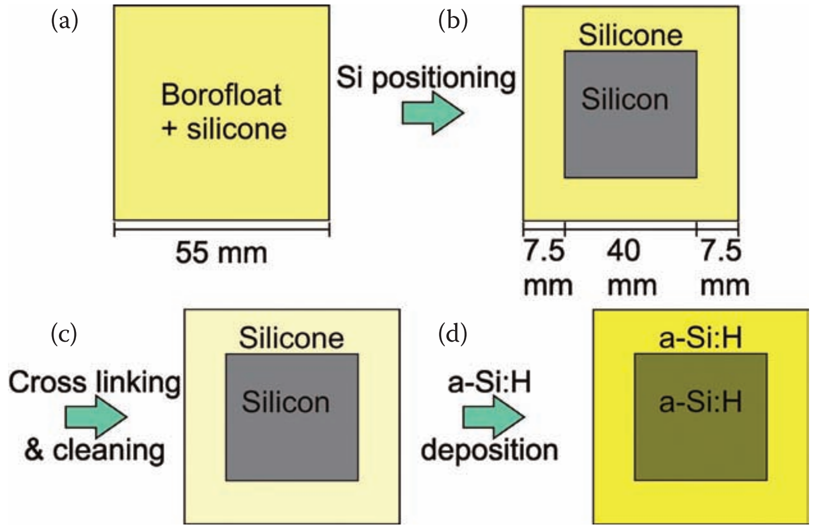

Figure 6. Process flow of the passivation process in the presence of uncovered silicone – schematical top view: (a) depositing of silicone to completely cover a Borofloat glass; (b) gluing of a one-side-passivated FZ Si sample onto the silicone, passivated side downwards; (c) cross-linking of the silicone accelerated by heat, and wet-chemical cleaning of the sample stack; (d) a-Si:H deposition.

For the first method, spatially resolved lifetime mappings are carried out using the microwave-detected photoconductivity decay (MWPCD) technique (WT-2000 by Semilab) [41,42]. The lifetime mappings show the quality of the passivation layer to a spatial resolution of 500µm. Local influences in the vicinity of the glue can be detected in a degradation of the lifetime close to the silicone.

For the second method, lifetime measurements using the quasi-steady-state photoconductance (QSSPC) method are performed [43]. In contrast to the MWPCD technique, this method does not provide a spatially resolved mapping, but allows the lifetime to be determined as a function of minority-carrier density. The surface recombination velocity (SRV) of the a-Si:H layers deposited in the presence of two-part silicones is calculated from the QSSPC measurements. The SRV quantifies the passivation quality and thus the potential outgassing effect of these silicones (which were not specifically developed for such processes).

To demonstrate the applicability of the gluing procedure to ultrathin silicon wafers, 30µm-thick silicon layers from a layer transfer with porous Si were used. One side was passivated with a silicon nitride layer; this side was then glued to a Borofloat glass using silicone. Fig. 4 shows the sample stack. After surface conditioning and cleaning, the thin Si layers received, on the rear side, an a-Si:H layer at 250°C for passivation.

Fig. 5 shows the MWPCD mapping of two epitaxial layers glued to Borofloat glasses using two different two-part silicones. The passivation quality is reduced, mainly near the edges of the samples, where the distance to the encapsulation material is small. The detrimental influence is significantly lower in the sample using silicone A (left) than in the sample using silicone B (right). With silicone A the effective lifetime is more homogeneous, and there is a decrease in effective lifetime at two of the four edges. The affected area is, however, limited to the region within 3mm of the edge.

To determine the SRV the experiments were carried out with floatzone (FZ) Si wafers. The influence of uncovered silicones on the passivation quality was investigated. Fig. 6 shows the process flow for the passivation process in the presence of uncovered silicone. First, silicone is deposited on Borofloat glass of dimensions 55mm × 55mm (Fig. 6(a)). Next, a one-side SiN_x-passivated FZ Si sample of dimensions 40mm × 40mm is glued to the centre of the Borofloat glass (Fig. 6(b)). Cross-linking then occurs and the stack is wet-chemically cleaned (Fig. 6(c)). Finally, the FZ Si and the surrounding silicone receive an a-Si:H layer (Fig. 6(d)).

It was determined that the SRV is reduced by one to two orders of magnitude if uncovered silicones are present during the a-Si:H passivation. This indicates that the reduction of the passivation quality is caused by volatile components that leak from the exposed silicones when subjected to the effects of heat, vacuum and plasma. These components may contaminate the Si surface or interact with the precursors of the a-Si:H deposition process.

An additional pre-outgassing (i.e. the heating of the glued FZ Si wafer for two minutes at the process temperature and pressure of the subsequent a-Si:H deposition) was found to reduce the detrimental effects on the passivation layer. The best passivation was determined for silicone A with S_{rear} = (2.5±1.5)cm/s measured by the QSSPC method at the minority-carrier density $\Delta n = 10^{15}\text{cm}^{-3}$. Hence, this silicone allows an SRV of the a-Si:H layer as low as that for non-glued samples. Addition-curing two-part silicones are therefore promising candidates for module-level processing.

> “An additional pre-outgassing was found to reduce the detrimental effects on the passivation layer.”

Conclusion

The commonly used encapsulant EVA is a well-established low-cost material for standard applications in the field of c-Si PV. Thermoplastic materials, however, offer advantages such as a faster processing time and a higher stability and transparency. The balance between the cost structure of the new materials and the higher power output or the superior resistance to PID offered by their use will determine their success.

Recent novel hybrid silicon PV module concepts seek to combine the advantages of thin-film technologies with those of wafer technologies; however, additional requirements that are fundamentally different from those used for standard PV modules are imposed on encapsulants. One such requirement is that the encapsulant must be compatible with module-level processing. In particular, the a-Si:H deposition that is necessary for passivation or hetero-emitter formation is very sensitive to the presence of unsuitable encapsulants. It was shown that suitable silicone-based encapsulants enable the use of such module-level processes. Future work on even slimmer module-level processing sequences will show if cost-competitiveness with EVA and conventional module concepts can be achieved. There are, however, no technological obstacles to realizing the potential of the novel module concepts.

Acknowledgements

The authors thank H. Fischer for her valuable help with sample preparation, as well as R. Winter and A. Knorr for their help with processing. We are grateful for the financial support from REC ASA.

References

[1] McIntosh, K.R. et al. 2009, “An optical comparison of silicone and EVA encapsulants for conventional silicon PV modules: A ray-tracing study”, *Proc. 34th IEEE PVSC*, Philadelphia, Pennsylvania, USA, pp. 544–549.

[2] Morlier, A. et al. 2013, “Influence of the curing state of ethylene-vinyl acetate on photovoltaic modules aging”, *Proc. 28th EU PVSEC*, Paris, France.

[3] Kempe, M.D. et al. 2007, “Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices”, *Solar Energy Mater. & Solar Cells*, Vol. 91, No. 4, pp. 315–329.

[4] Kajari-Schröder, S. et al. 2010, “Modelling the curing dynamics of ethylene-vinyl acetate”, *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 4039–4043.

[5] Schulze, K. et al. 2012, “Untersuchung von Alterungseffekten bei monokristallinen PV-Modulen mit mehr als 15 Betriebsjahren durch Elektrolumineszenz- und Leistungsmessung”, *Proc. 28. OTTI Symp. Photovolt. Solarenergie*, Staffelstein, Germany, pp. 194–195.

[6] Green, M.A. 2005, “Silicon photovoltaic modules: A brief history of the first 50 years”, *Prog. Photovolt.: Res. Appl.*, Vol. 13, No. 5, pp. 447–455.

[7] Dow Corning Corporation 1978, “Develop silicone encapsulation systems for terrestrial silicon solar arrays”, Doe/JPL954995-2.

[8] Henderson, A.H. 1993, “Ethylene-vinyl acetate (EVA) copolymers: A general review”, *IEEE Electr. Insul. Mag.*, Vol. 1, No. 9, pp. 30–38.

[9] Czanderna, A.W. et al. 1996, “Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review”, *Solar Energy Mater. & Solar Cells*, Vol. 43, No. 2, pp. 101–181.

[10] Kojima, T. et al. 2005, “Ultraviolet-ray irradiation and degradation evaluation of the sealing agent EVA film for solar cells under high temperature and humidity”, *Solar Energy Mater. & Solar Cells*, Vol. 85, No. 1, pp. 63–72.

[11] Pern, F.J. 1996, “Factors that affect the EVA encapsulant discoloration rate upon accelerated exposure”, *Solar Energy Mater. & Solar Cells*, Vol. 41/42, pp. 587–615.

[12] McIntosh, K.R. et al. 2011, “The effect of damp-heat and UV aging tests on the optical properties of silicone and EVA encapsulants”, *Prog. Photovolt.: Res. Appl.*, Vol. 19, No. 3, pp. 294–300.

[13] Powell, N. et al. 2010, “Improved spectral response of silicone encapsulated photovoltaic modules”, *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA, pp. 2791–2794.

[14] Kempe, M.D. et al. 2009, “Accelerated stress testing of hydrocarbon-based encapsulants for medium-concentration CPV applications”, *Proc. 34th IEEE PVSC*, Philadelphia, Pennsylvania, USA, pp. 1826–1831.

[15] Weber, U. et al. 2012, “Acetic acid production, migration and corrosion effects in ethylene-vinyl-acetate- (EVA-) based PV modules”, *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 2992–2995.

[16] Peike, C. et al. 2013, “Origin of damp-heat induced cell degradation”, *Solar Energy Mater. & Solar Cells*, Vol. 116, pp. 49–54.

[17] Miller, D.C. et al. 2013, “Durability of polymeric encapsulation materials for concentrating photovoltaic systems”, *Prog. Photovolt.: Res. Appl.*, Vol. 21, No. 4, pp. 631–651.

[18] Allen, N.S. et al. 2001, “Aspects of the thermal oxidation, yellowing and stabilization of ethylene vinyl acetate copolymer”, *Polym. Degrad. Stabil.*, Vol. 71, pp. 1–14.

[19] Hahn, G. 2012, “Status of selective emitter technology”, Proc. 25th EU PVSEC, Valencia, Spain, pp. 1091–1096.

[20] Schmid, C. et al. 2012, “Impact of high light transmission EVA-based encapsulant on the performance of PV modules”, *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3494–3498.

[21] Naumann, V. et al. 2012, “Micro structural root cause analysis of potential induced degradation in

c-Si solar cells", *Energy Procedia*, Vol. 27, pp. 1–6.

[22] Koch, S. et al. 2012, "Potential induced degradation effects on crystalline silicon cells with various antireflective coatings", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1985–1990.

[23] Mehlich, H. et al. 2012, "A new method for high resistance against potential induced degradation", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3411–3413.

[24] Koch, S. et al. 2012, "Encapsulation influence on the potential induced degradation of crystalline silicon cells with selective emitter structures", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 1991–1995.

[25] Lechner, P. et al. 2012, "Estimation of time to PID-failure by characterisation of module leakage currents", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3152–3156.

[26] SEMI PV Group 2013, "International technology roadmap for photovoltaic (ITRPV): Results 2012" [http://www.itrpv.net/Reports/Downloads/2013/].

[27] Cárabe, J. & Gandia, J.J. 2004, "Thin-film-silicon solar cells", *Opto-Electron. Rev.*, Vol. 12, No. 1, pp. 1–6.

[28] Brendel, R. et al. 2011, "High-efficiency cells from layer transfer: A first step toward thin-film/wafer hybrid silicon technologies", *IEEE J. Photovolt.*, Vol. 1, No. 1, pp. 9–15.

[29] Powell, D.M. et al. 2012, "Crystalline silicon photovoltaics: A cost analysis framework for determining technology pathways to reach baseload electricity costs", *Energy Environ. Sci.*, Vol. 5, No. 3, pp. 5874–5883.

[30] Brendel, R. & Auer, R. 2001, "Photovoltaic mini-modules from layer transfer by the porous silicon process", *Prog. Photovolt.: Res. Appl.*, Vol. 9, No. 6, pp. 439–443.

[31] Brendel, R. 1997, "A novel process for ultrathin monocrystalline silicon solar cells on glass", *Proc. 14th EU PVSEC*, Barcelona, Spain, pp. 1354–1357.

[32] Tayanaka, H. et al. 1998, "Thin-film crystalline silicon solar cells obtained by separation of a porous silicon sacrificial layer", *Proc. 2nd World Conf. PV Solar Energy Conv.*, Vienna, Austria, pp. 1272–1277.

[33] Govaerts, J. et al. 2013, "Development of a-Si:H/c-Si heterojunctions for the i^2-module concept: Low-temperature passivation and emitter formation on wafers bonded to glass", *Solar Energy Mater. & Solar Cells*, Vol. 113, pp. 52–60.

[34] van Roosmalen, J. et al. 2012, "Crystalline silicon interconnected strips (XIS): Introduction to a new, integrated device and module concept", *Energy Procedia*, Vol. 27, pp. 604–609.

[35] Mewe, A. et al. 2013, "XIS: A low-current, high-voltage back-junction back-contact photovoltaic device", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA.

[36] Brendel, R. et al. 2013, "Recent progress and options for future crystalline silicon solar cells", *Proc. 28th EU PVSEC*, Paris, France.

[37] Petermann, J.H. et al. 2013 [in preparation].

[38] Petermann, J. H. et al. 2013, "Module interconnection of both sides-contacted silicon solar cells by screen-printing", *Proc. 39th IEEE PVSC*, Tampa, Florida, USA.

[39] Steckenreiter, V. et al. 2013, "Qualification of encapsulation materials for module-level-processing", *Solar Energy Mater. & Solar Cells* [in press], DOI: 10.1016/j.solmat.2013.06.012.

[40] Kempe, M.D. 2010, "Evaluation of encapsulant materials for PV applications", *Photovoltaics International*, 9th edn, pp. 170–176.

[41] Kunst, M. & Beck, G. 1986, "The study of charge carrier kinetics in semiconductors by microwave conductivity measurements", *J. Appl. Phys.*, Vol. 60, No. 10, pp. 3558–3556.

[42] Kunst, M. & Beck, G. 1988, "The study of charge carrier kinetics in semiconductors by microwave conductivity measurements. II.", *J. Appl. Phys.*, Vol. 63, No. 4, pp. 1093–1098.

[43] Sinton, R.A. & Cuevas, A. 1996, "Contactless determination of current–voltage characteristics and minority-carrier lifetimes in semiconductors by quasi-steady-state photoconductance data", *Appl. Phys. Lett.*, Vol. 69, No. 17, pp. 2510–2512.

About the Authors

Verena Steckenreiter received her diploma degree in environmental protection from the University of Applied Sciences Bingen, Germany, in 2007. In 2008 she joined the Si thin-film technology group at the Institute for Solar Energy Research Hamelin (ISFH), where she has headed projects on alternative module-interconnection concepts since 2011. Her current areas of focus are module-level processing and kerf-less technologies.

Arnaud Morlier studied chemistry and received his Ph.D. in materials science from the Joseph Fourier University of Grenoble in France, specializing in thin-film polymer solar cell encapsulation. Since 2011 he has been working in the module and interconnection technology group at ISFH, focusing on material degradation in modules.

Marc Köntges received his Ph.D. in physics from the University of Oldenburg, Germany, in 2002 for his research in thin-film solar cells. From 2002 to 2005 he led the thin-film technology group at ISFH, and then became the head of the module and interconnection technology group. He is currently working on the development of characterization and production methods for PV modules.

Sarah Kajari-Schröder received her diploma degree in physics in 2004 and her Ph.D. in 2009 from the University of Ulm. She then joined the PV module group at ISFH, where the direction of her research was crack formation in solar cells, and the mechanical stability and reliability of PV modules. Since 2011 she has headed the silicon thin-film group at ISFH, focusing on the fabrication, handling and interconnection of ultrathin crystalline silicon wafers, cells and modules.

Rolf Brendel received his physics degree in 1987 from the University of Heidelberg and his Ph.D. in material science from the University of Erlangen. He worked on Si solar cells at the Max Planck Institute for Solid State Research and at the Bavarian Centre for Applied Energy Research. In 2004 he became a full professor of physics at the Leibniz University of Hanover and the director of the Institute for Solar Energy Research Hamelin (ISFH).

Enquiries

Verena Steckenreiter
ISFH
Am Ohrberg 1
D-31860 Emmerthal
Germany

Tel: +49 (0) 5151 999 325
Email: v.steckenreiter@isfh.de
Website: www.isfh.de