INCREASED INTERNAL QUANTUM EFFICIENCY OF ENCAPSULATED SOLAR CELLS BY USING TWO-COMPONENT SILICONE AS ENCAPSULANT MATERIAL

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ABSTRACT: Two-component silicone encapsulation materials show a higher transmission in the short wavelength region compared to EVA (ethylene vinyl acetate) encapsulation material. This property leads to an enhanced blue response of the encapsulated solar cells and therefore an increase in J_{sc} (short circuit current density) is expected. Selective emitter and homogeneous emitter solar cells have been encapsulated with silicone materials as well as with EVA, and the IQE (internal quantum efficiency) of all cells before and after encapsulation was determined. A significant gain in IQE for wavelengths below 380 nm was observed for cells encapsulated with silicone compared to those with EVA. We estimate that that the improved blue response of the cells encapsulated with silicone results in a possible gain in J_{sc} of up to 1.3 % for the selective emitter cells.

Keywords: Encapsulation, Silicone, Internal quantum efficiency, Selective emitter

1 APPROACH

Different silicone compound materials have been analyzed regarding transmission, reflectivity, and processing characteristics. We have chosen two different industrially available two component silicones and have encapsulated the front side of selective emitter solar cells as well as standard emitter solar cells with silicone encapsulants and EVA, respectively, using standard module glass. The rear sides of the cells were not encapsulated in order to be able to perform the following measurements before and after encapsulation: after measuring the IV characteristic of the cells (respective modules), the external quantum efficiency and the reflection of the cells (respective modules) was measured and the internal quantum efficiency was determined.

2 PROPERTIES OF SILICONE MATERIALS

Silicone elastomers and gels are industrially available and find application for device encapsulation as well as for PV module encapsulation. The silicones used in this examination consist of two components, one containing a platinum catalyst, the other the crosslinker. In general, silicones can be formulated to cover a wide range of cure characteristics; in particular the hardness of the cured material can vary from very soft and gel-like over a harder but flexible elastomer to a hard resinous consistency. The curing time is temperature dependant, curing within minutes can be achieved by elevating the temperature up to 150 °C. Critical characteristics of silicones for the use as solar cell encapsulant are among other properties the transmission characteristics, UV stability, temperature and humidity stability, and adhesion to cells and encapsulant materials. For the tests in this investigation we have chosen one silicone material which cures to a rather sticky gel (in the following referred to as silicone A) and one silicone which has a medium cured hardness (silicone B). To enhance the adhesion to glass of the second material, a primer containing silicone resins is applied to the glass before pouring the silicone. Both materials have been processed at room temperature without the use of vacuum, nevertheless we were able to achieve very good results, and nearly bubble free encapsulation of single solar cells.

In this investigation we concentrated on the fact that silicone shows a very good transmission of light in the short wavelength region which is comparable to the transmission of the module glass. In comparison to silicone as module encapsulant, EVA will cut off any light below 380 nm.

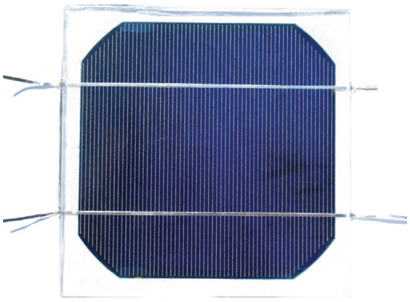

Figure 1: Photograph of a homogenous emitter solar cell embedded in Silicone A

2.1 Transmission of silicone

We measured the transmission as well as the reflection of two types of silicone and EVA applied on module glass using a Cary UV-Vis-NIR Spectrophotometer. The samples for these measurements were prepared by laminating EVA or applying silicone onto one module glass plate (thickness 3.2 mm). The thickness of the EVA and the silicone layers is less than 1 mm. Note that the measured stack is air-glass-encapsulant-air.

The refractive index of silicone is $N_D^{25}\,_{\text{Silicone A}} = 1.404$, $N_D^{25}\,_{\text{Silicone B}} = 1.407$ for the first component respectively $N_D^{25}\,_{\text{Silicone B}} = 1.400$ for the second component. The results of the transmission measurements are presented in figure 1.

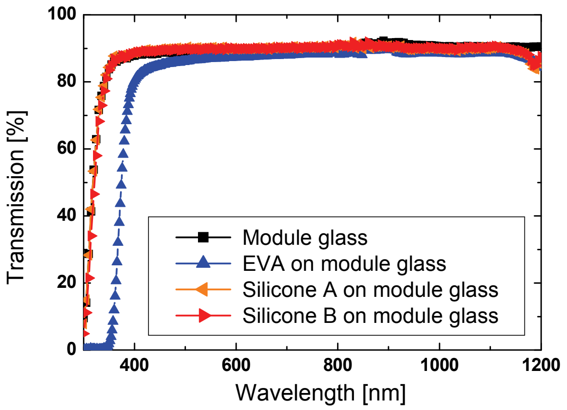

Figure 1: Transmission of two component silicone on module glass compared to EVA on module glass. Silicone compound encapsulants show a high transmission in the short wavelength region. EVA has a UV cut-off below 380 nm.

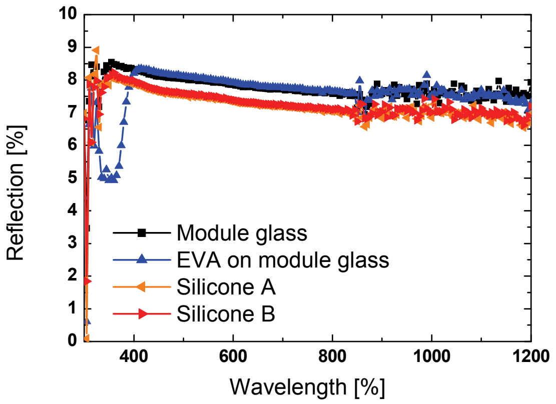

Figure 2: Reflection of two component silicone compared to EVA (both on module glass).

2.2 Damp-heat tests (DHT) of silicone

Four samples were prepared similarly to the samples of the transmission tests described in section 2.1 and transmission and reflectivity were measured with the Cary Spectrophotometer. Then two of the samples were exposed to 85 °C and 85 % rel. humidity for 1000 h, meanwhile the other two samples were stored in the laboratory at room temperature and ambient humidity. All samples were measured again; the results are represented in figure 3.

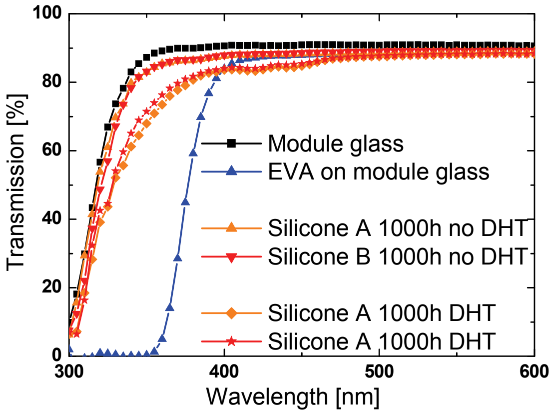

Figure 3: Transmission of two component silicone on module glass after 1000 h exposition to 85 °C and 85 % rel. humidity or storing in laboratory conditions.

3 ELECTRICAL CHARACTERIZATION AND ENCAPSULATION OF SOLAR CELLS

3.1 Solar cell material

Two types of solar cells have been used in this study: homogenous emitter solar cells and selective emitter solar cells. The latter are especially valuable to test the good transmission characteristics of silicone materials as selective emitter solar cells show a better blue response than standard homogenous solar cells. Solar cells used in this study have been processed on 1.5 Ωcm monocrystalline Czochralski material (cell size 125 x 125 mm^2). The process for homogeneous emitter cells used at University of Konstanz is a standard industrial-type one: after alkaline texturing in KOH/IPA and cleaning, a 50 Ω/sq. $POCl_3$ emitter was diffused followed by PECVD SiN_x deposition. Screen printing of Ag paste on the front and Al on the back side was followed by co-firing in a belt furnace. Edge isolation was performed using a wafer dicing saw. The selective emitter cells have been processed using a novel processing scheme currently under investigation at University of Konstanz based on wet chemical etching [2]. Cu-interconnections were soldered by hand onto the busbars of all cells in order to perform electrical characterization after encapsulation. The Cu interconnect ribbon has a composition of Sn62Pb36Ag2, typical for industrial module production and soldering flux IF 2005 M was used to treat busbars and ribbon before soldering.

3.2 Electrical characterization

After all processes involving elevated temperature steps (metal firing step, soldering of the tabbing, and lamination with EVA) the cells have been degraded in order to obtain comparable electrical characteristics. IV-measurements have been performed before soldering the interconnection ribbons, before encapsulation of the cells with EVA or silicone and after cell encapsulation under one-sun illumination and temperature control to 25 °C.

Spectral response measurements have been performed after soldering the interconnection ribbons (before embedding the cells into silicone or EVA) and after encapsulation. The chuck of the IV-measurement equipment was covered with the same black mask posed around the cells before encapsulation and on the one-cell modules after lamination to avoid any additional light trapping by the glass layer which is larger than the cell area.

3.3 Encapsulation of the solar cells

The two cell types described above were encapsulated in three different materials: EVA, silicone A and silicone B. The front side of the encapsulated cells is covered with a commercially available module glass (thickness 3.2 mm) followed by a layer of encapsulation material. The rear sides of the encapsulated cells are open in order to enable the contact to the chuck during IV- and SR-measurements.

The lamination with EVA was performed in a laminator for single cell modules designed at the University of Konstanz with commercially available EVA. Some of the cells embedded in silicone were stabilized on a vacuum chuck during the curing process to ensure the flatness of the cells. The two component silicone was processed and cured under room temperature without vacuum. To ensure a bubble free encapsulation, a thin layer of the liquid was applied on the cell surface and the glass before carefully posing both materials on top of each other.

Altogether 12 single-cell modules have been prepared by embedding the solar cells in silicone respective by laminating in EVA, using commercially available module glass as cover (see table 1).

Table I: Overview of samples prepared.

	Homogenous emitter cell	Selective emitter cell
EVA	2	2
Silicone A	3	3
Silicone B	1	1

4 RESULTS

4.1 Spectral response measurements

An area of 10 x 10 cm^2 (including the busbars) of the cell before encapsulation was scanned to determine external quantum efficiency (EQE) and reflection. From these measurements the IQE was calculated. The same measurements and calculation were performed after encapsulation on the system consisting of glass, encapsulant, and cell. In this way the IQE of the encapsulated cell includes absorption in the glass and the encapsulation material.

4.2 Spectral response measurements before encapsulation

For both selective and standard emitter cells encapsulated in two component silicone, a significant gain in IQE for wavelengths below 380 nm was observed in comparison to the cells encapsulated in EVA (see figure 4).

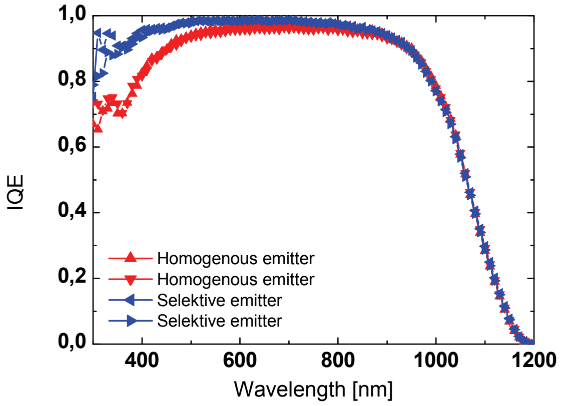

Figure 4: IQE before encapsulation
The graph shows the results of IQE measurements for selective emitter and homogeneous emitter cells before encapsulation. The IQE data is normalized with J_{sc} of the cells obtained by the IV-measurements.

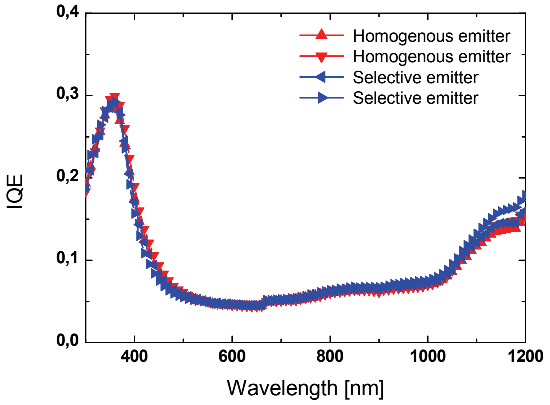

Figure 5: Reflection measurements for selective emitter and homogeneous emitter cells before encapsulation.

4.3 Spectral response measurements after encapsulation

Both selective emitter cells and solar cells processed with homogenous emitter embedded in silicone show a better IQE below 400 nm than cells laminated with EVA (see figure 6 to 8).

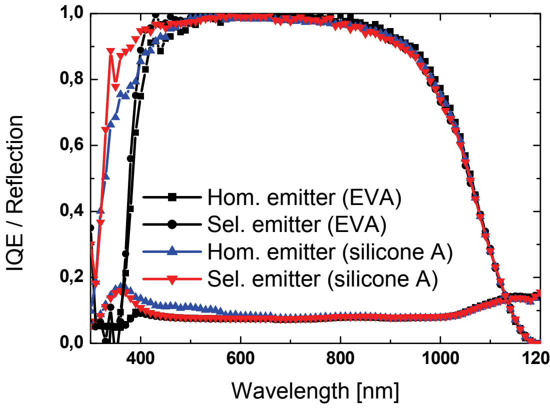

Figure 6: IQE and reflection after encapsulation
Internal quantum efficiency of selective emitter cells and homogenous cells (standard emitter process) after encapsulation with different materials (EVA and silicone A).

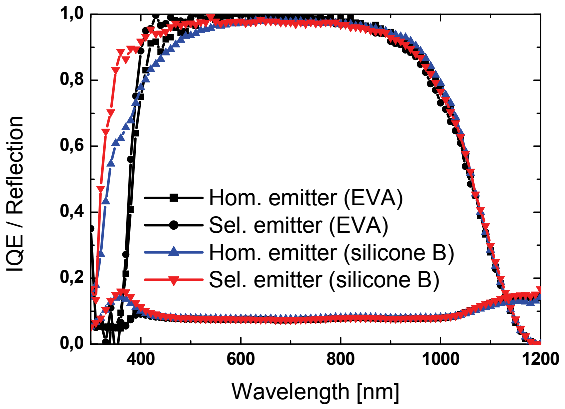

Figure 7: IQE and reflection after encapsulation
Internal quantum efficiency of selective emitter cells and homogenous cells (standard emitter process) after encapsulation with different materials (EVA and silicone B).

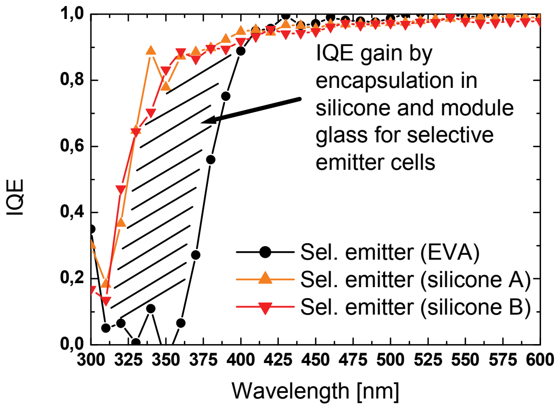

Figure 8: IQE after encapsulation (detail)
The details of the IQE plot from figure 6 and figure 7 shows the gain in transmission for selective emitter cells which have been encapsulated in silicone compound material and module glass. EVA cuts off UV-light below 380 nm.

4.4 Calculated gain in short circuit current density

If we assume that every photon can create one electron, all incoming photons with wavelengths from 295 nm to 1200 nm could theoretically produce a current density of 42 mA/cm^2 [3].

According to the results of the transmission measurements EVA has a cut-off in transmission at 380 nm (see figure 9). We can estimate the gain in short circuit current density for different encapsulation materials using the EQE and the incoming photon flux. Therefore we use the difference $\Delta EQE = EQE(\text{Silicone}) - EQE(\text{EVA})$. We can then integrate over the product of ΔEQE and the photon flux $F(\lambda)$ between 300 nm and 400 nm multiplied by the electron charge q.

$$\Delta J = \int_{300nm}^{400nm} \Delta EQE(\lambda) \cdot q \cdot F(\lambda) d\lambda$$

The results of these calculations are displayed in table II and table III. (Two runs have been performed, one in 2007 and one 2008).

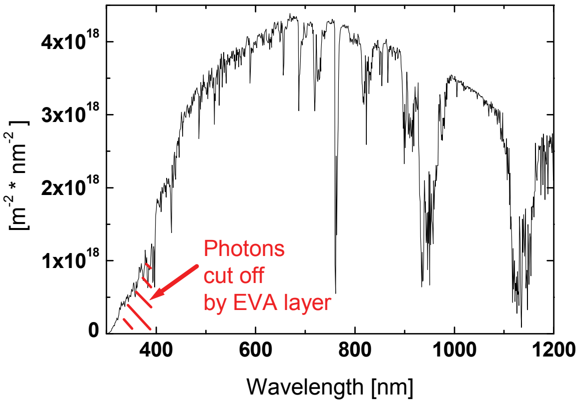

Figure 9: Photon flux calculated from AM1.5 spectrum [3]

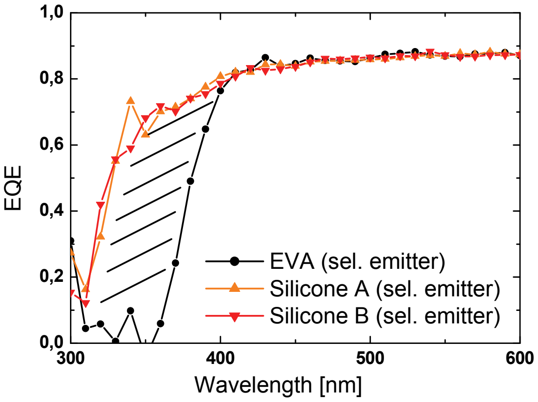

Figure 10: EQE of a selective emitter cell before and after encapsulation.

Table III: Current density gain for encapsulation in silicone instead of EVA (selective emitter solar cells).

Selective Emitter	**$\Delta J_{sc,calc}$ $[mA/cm^2]$**	**$\Delta J_{sc,calc}$ [% of $J_{sc,cell}$]**
Silicone A (2007)	0.34	0.95
Silicone B (2007)	0.33	0.92
Silicone A (2008)	0.35	0.96
	0.36	1.00

Table IV: Current density gain for encapsulation in silicone instead of EVA (homogeneous emitter solar cells).

Homogenous Emitter	**ΔJ_{sc} calc. $[mA/cm^2]$**	**$\Delta J_{sc,calc}$ [% of $J_{SC,cell}$]**
Silicone A (2007)	0.32	0.92
Silicone B (2007)	0.27	0.76
Silicone A (2008)	0.32	0.87
	0.31	0.85

4.5 IV-measurements

Taking into consideration the systematic error of our IV-measurement and the fact that it is not possible to make statistical evaluations given the relatively small amount of samples, it is obvious that it is difficult to measure the absolute J_{sc} increase on the fabricated one-cell modules. (Note: the illumination of the IV-measurement was calibrated to one sun with the same reference cell for measurements before and after encapsulation.)

The current density measured on the cells after soldering the Cu-ribbons is higher than the current measured on the encapsulated modules. The loss in J_{sc} after encapsulation compared to J_{sc} before encapsulation seems to be less for cells encapsulated in silicone for all cells but one; however, the variations are small compared to the measurement error (see tables V and VI). As we used the same calibration cell before and after encapsulation, the IV measurement-results of the modules include a larger error because of the increased spectral mismatch.

Table V: ΔJ_{sc} in [%] relative to measurements before encapsulation (samples prepared in 2007).

Encapsulant	**ΔJ_{sc} [%]**	**ΔJ_{sc} [%]**
Emitter	Selective	Homogenous
EVA	-2.4	-2.4
Silicone A	-1.9	-1.2
Silicone B	-2.1	-1.9

Table VI: ΔJ_{sc} in [%] relative to measurements before encapsulation (samples prepared in 2008).

Encapsulant	**ΔJ_{sc} [%]**	**ΔJ_{sc} [%]**
Emitter	Selective	Homogenous
EVA	-1.68	-0.6
Silicone A	-0.11 -1.14	+0.9 -0.8

5 CONCLUSIONS

Other materials for solar cell encapsulation than EVA have been successfully tested earlier and the advantages of an encapsulation technique with liquid silicone has been described [1] (e.g. vacuum-free encapsulation process with low energy consumption, possibility of repairing of damaged modules). In this report we showed that a further positive characteristic of silicone encapsulation is the gain in transmission in the short wavelength region and therefore a possibility to take full advantage of the elevated blue response of e.g. selective emitter solar cells [2]. Another advantage could be the possibility of combining the silicone encapsulants with inline module fabrication e.g. by using a roll lamination technique. UV-stability of the silicone encapsulant material is a critical issue and still has to be checked.

6 ACKNOWLEDGEMENTS

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