Influence of the PV-Module design and composition on the formed UV-Fluorescence patterns

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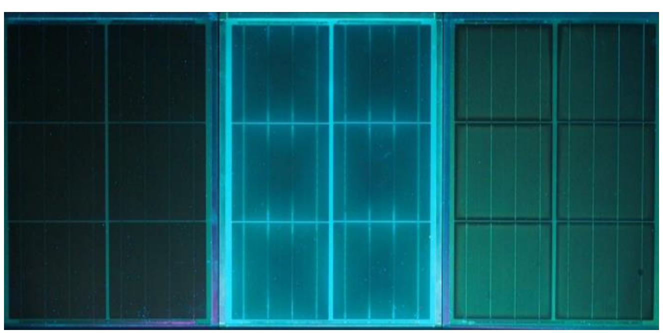
Indroduction

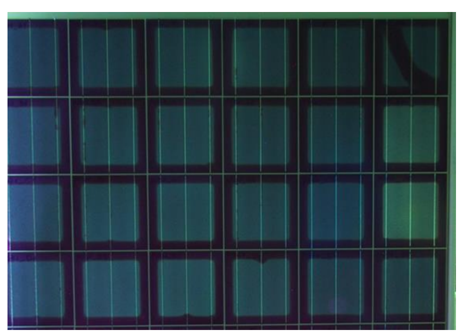
Reliability and durability of photovoltaic modules are a **key factor** for the development of emerging PV markets worldwide

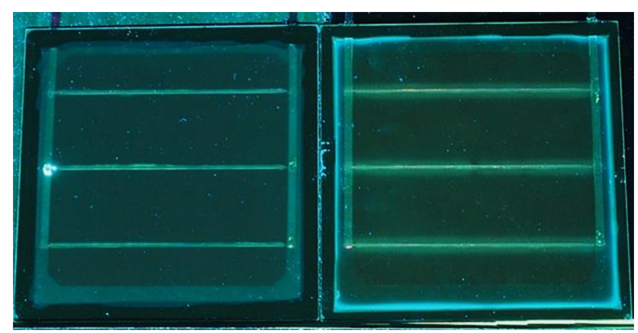
Reliability is directly dependent on the **chemical and physical stability** of the polymeric encapsulation materials

One method capable of **detecting ageing effects of the polymeric encapsulant** directly in the field is

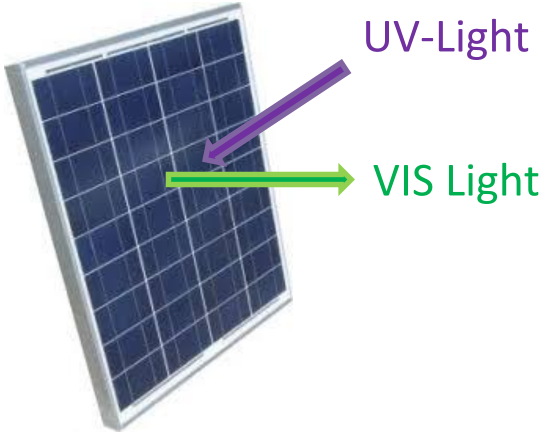
UV Fluorescence imaging

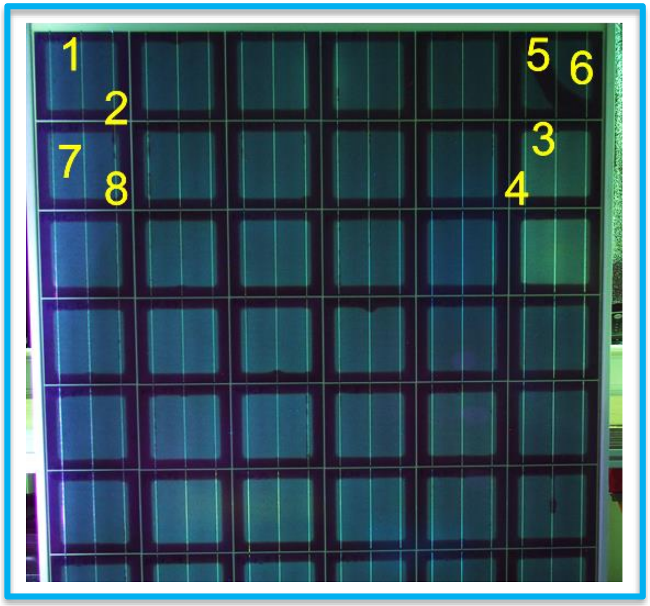




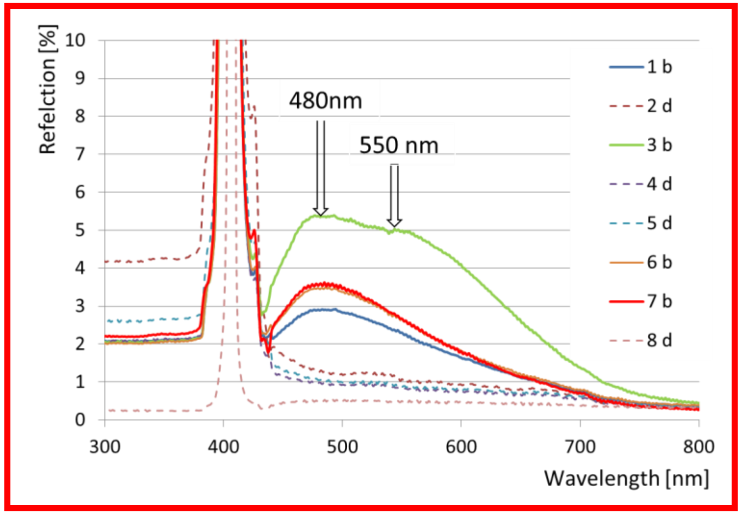


Measurement of UV-Fluorescence





- Excitation:
  UV-light source
- Detection :
  (i) eye or photographic camera
  → **image creating method**
  (ii) a probe connected to an UV/VIS spectrometer via an optical fibre
  → **spectroscopy** visualising the downshift of the reflected light



Equipment – UV-F Imaging

UV-Fluorescence **Imaging**

- non-invasive
- easy to handle (portable power supply)
- fast (exposure time ~ 30sec)

✓ UV-light source : three power- tuneable LED-arrays with an emission maximum at 365nm (50W, tunable) & low pass filter to cut off visible light

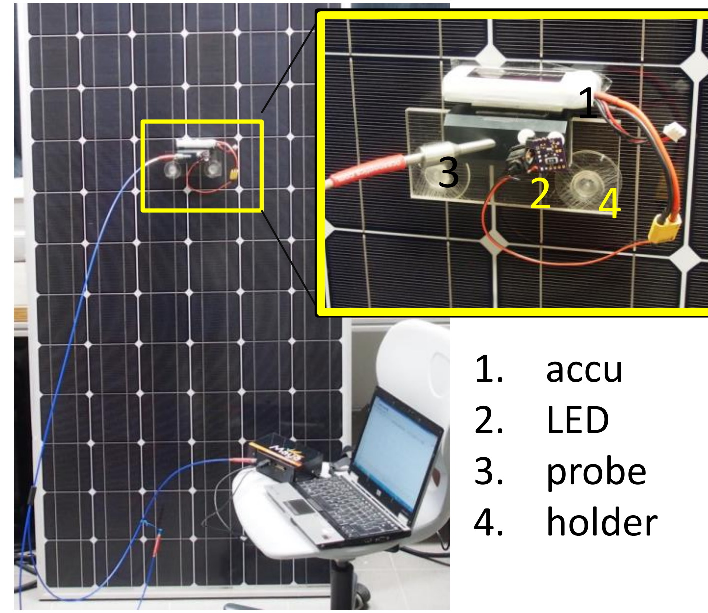
✓ Detection of UV-F: digital photographic camera (Olympus OM D) equipped with high pass filter to cut-off the UV-irradiation)

✓ Power supply : a modified DC/DC converter, sourced by a twelve cell Lithium-polymer-accumulator with a capacity of 5000 mAh

Equipment UV-F Spectroscopy

UV-Fluorescence **Spectroscopy**

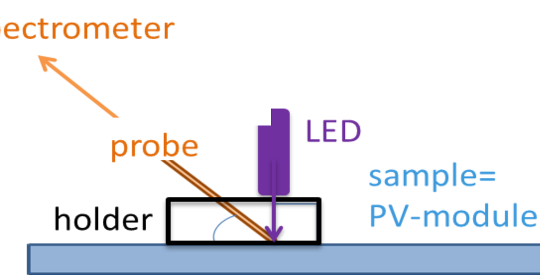
- non-destructive
- easy to handle
- outdoor & indoor measurements possible



1. accu
2. LED
3. probe
4. holder

✓ UV-light source

LED with an emission maximum at 365nm

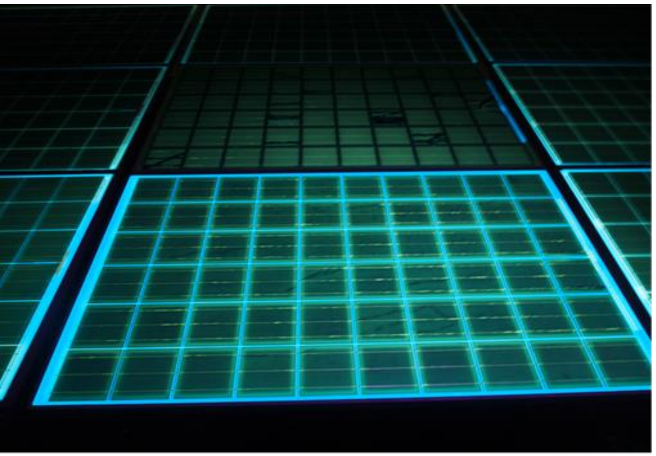


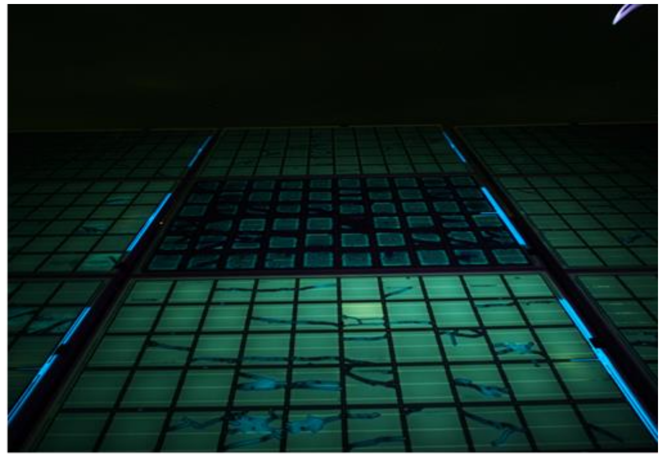
✓ Detection of UV-F

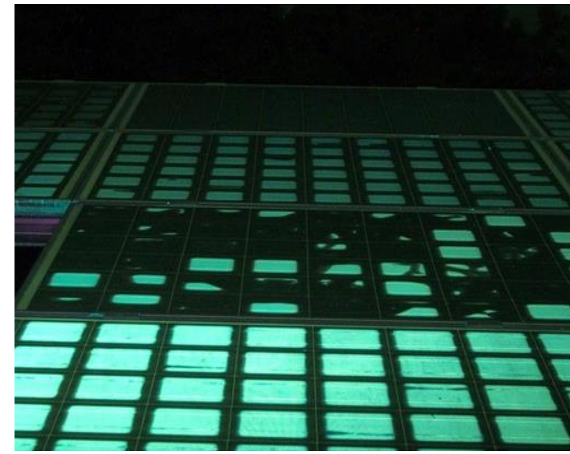
UV/VIS spectrometer Ocean Optics MAYA 2000 Pro (200-1100nm) with optical fibre ocean optics QR600-7-SR 125 BX

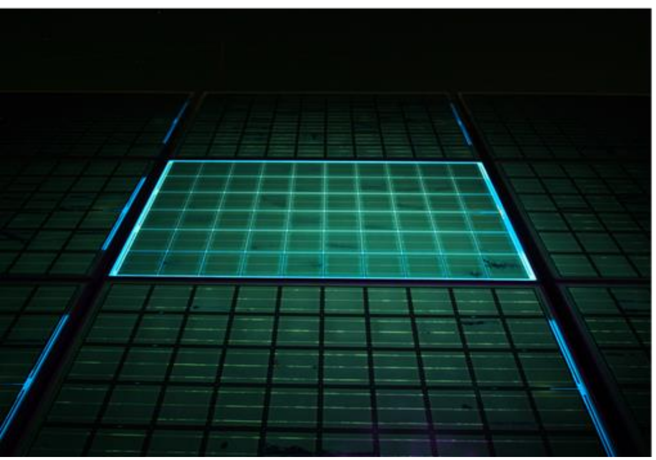
✓ **Power supply:** two cell Lithium-polymer-accumulator with a capacity of 1600 mAh for LED and notebook for spectrometer

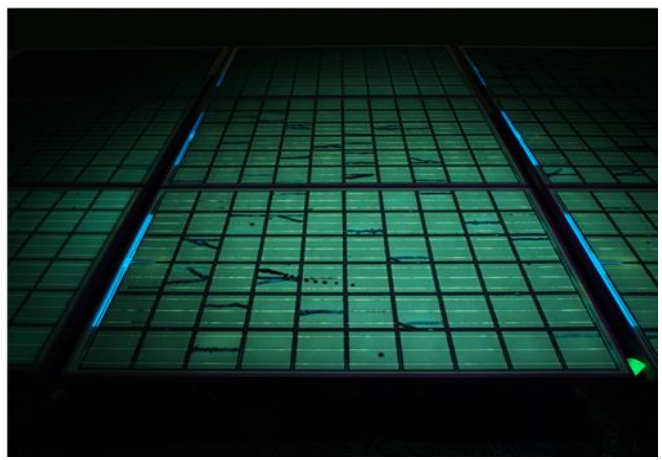
Fluorescence patterns / UV-F images





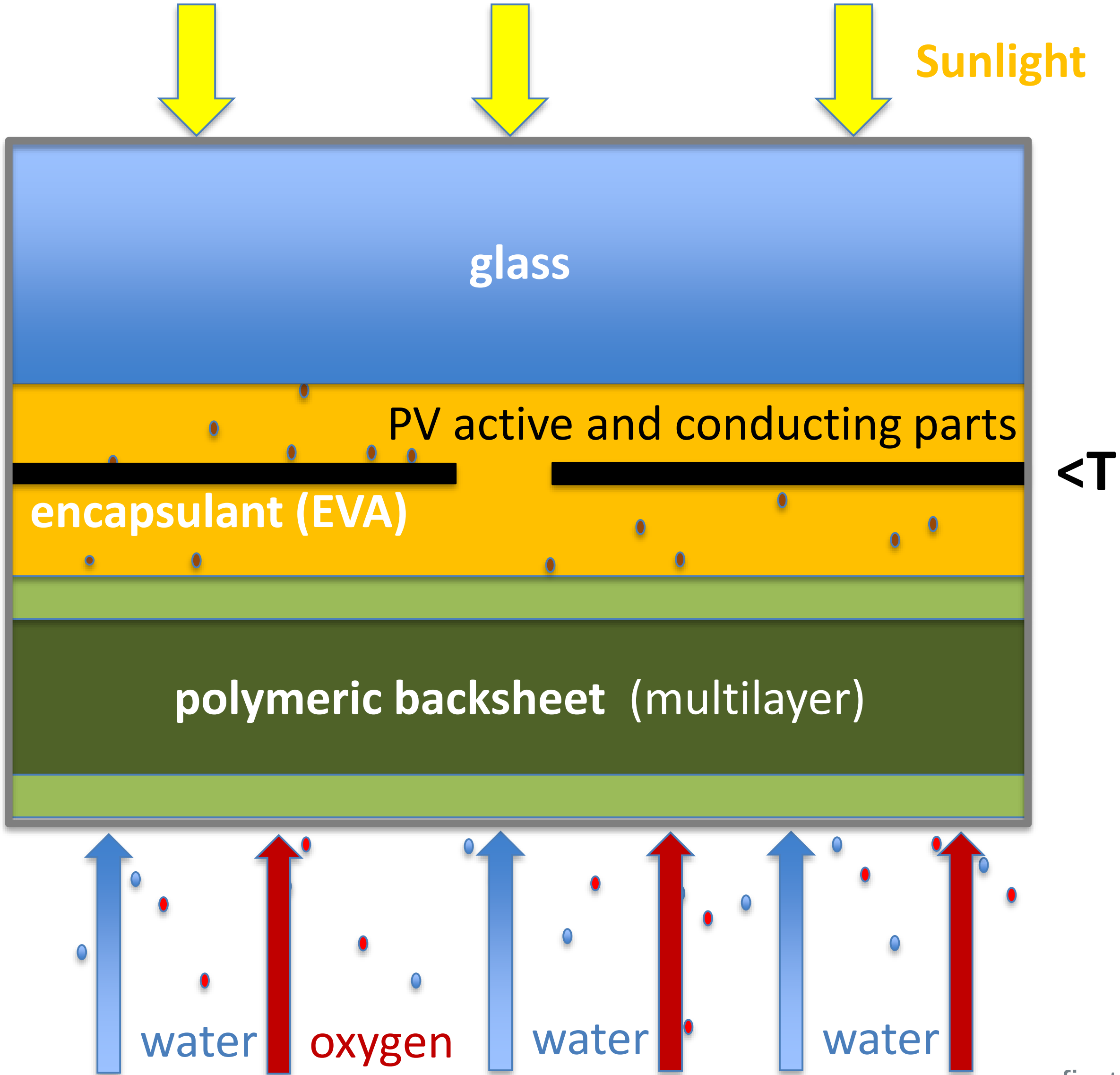




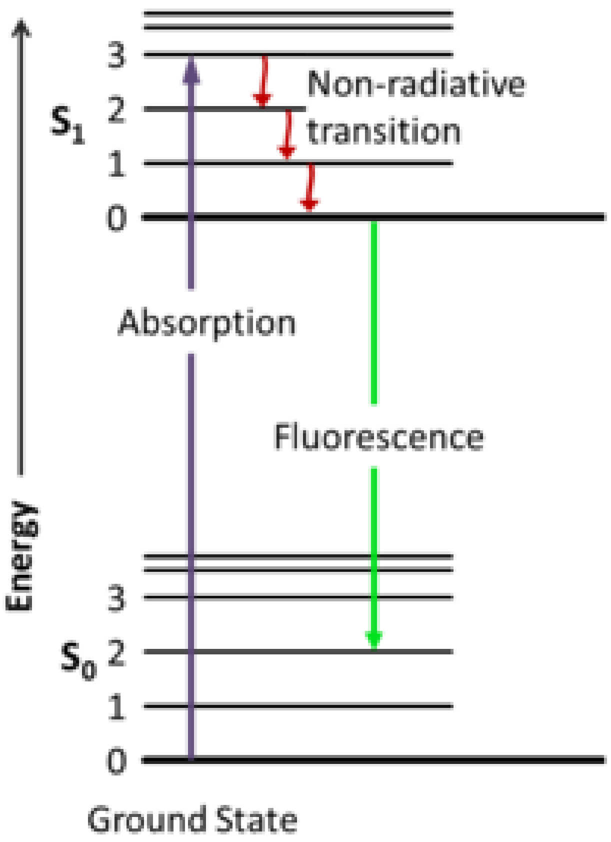


Influencing stress factors

In the field, PV-modules are exposed to various climatic stress factors like irradiance, temperature, humidity, …



Formation of Fluorescence



https://en.wikipedia.org/wiki/Jablonski_diagram

Fluorescence: emission of light by a material that has absorbed light or other electromagnetic radiation $\lambda_{\text{emitted light}} > \lambda_{\text{adsorbed light}}$

Fluorophore : fluorescent chemical compound that can re-emit light upon light excitation; mostly contains delocalized electrons (e.g. combined aromatic groups, plane or cyclic molecules with several π bonds or polymers in excited-state structure)

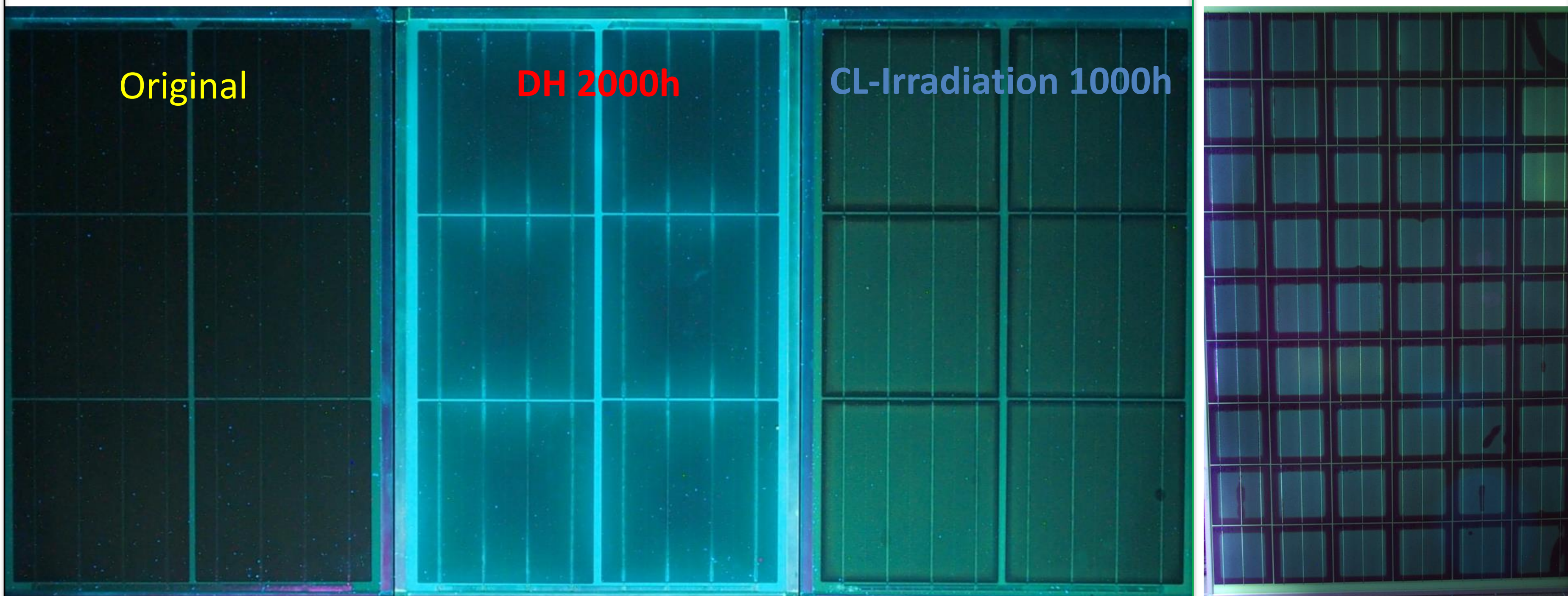
Typically: aeging/degradation products of additives and/or polymers or precursors thereof: *“activated molecules”*

Formation (different types) in the absence of O_2:

- Irradiation and elevated T (outdoors)
- high humidity and T (e.g. DH)
- high T (e.g. hot cells)

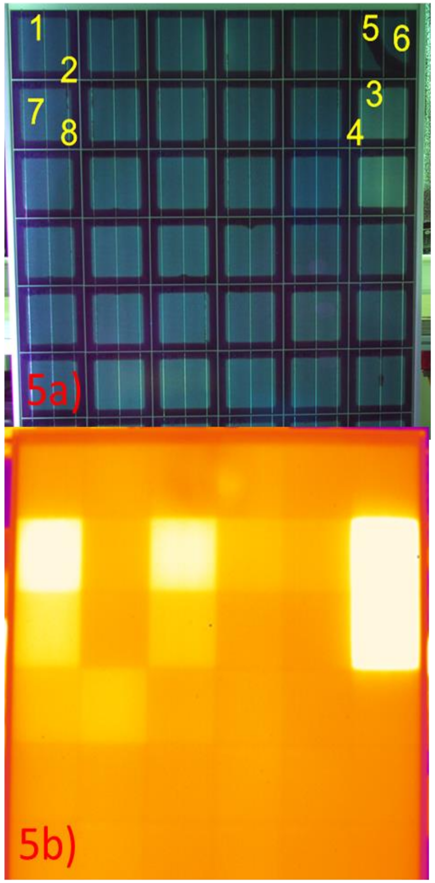
natural ↔ artificial ageing

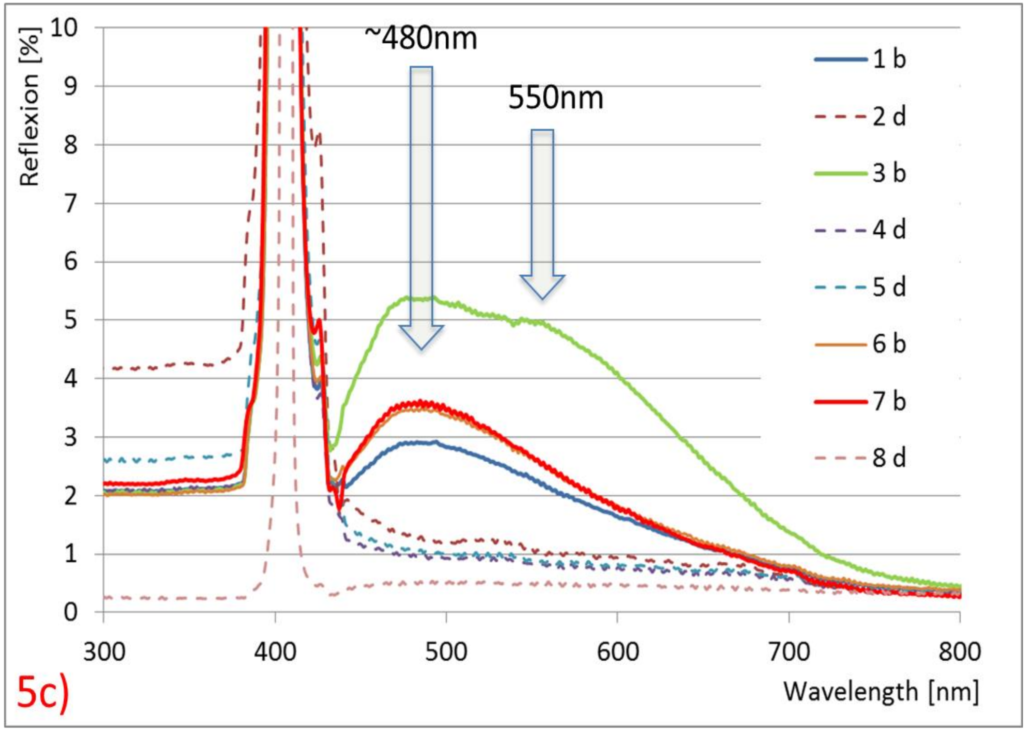
Accelerated ageing | Natural aging (5 y)



- DH-aging: UV-F above the backsheet and at outer regions of the cells
- CL-irradiation: homogeneous fluorescence over cells, extinctions at the rims
- Natural ageing: UV-F pattern comparable to the combined aging CL+I

Effect of stress factors

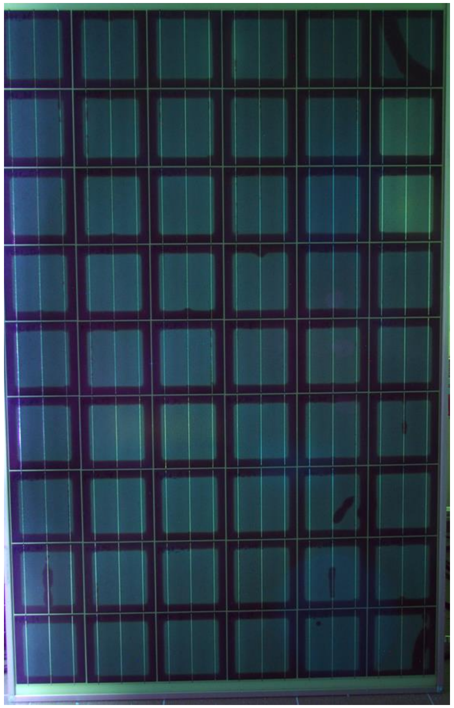




- ✓ peak ~480 nm - fluorescence generated upon environmental stress (irradiation, temperature, humidity)
- ✓ second peak ~550nm - additional thermal stress in the encapsulate (hot cells in thermographic image)

Fluoresence = Polymer Degradation? NO

Comparative analysis of EVA in parts with bright and dark fluorescence within a naturally aged PV-module:



Infrared spectroscopic analysis of EVA

No spectral differences caused by chemical degradation reactions detectable; only small shifts in wavenumber of some bands (e.g. changes in molecular environment)

Thermal analysis (DSC) of EVA

No indicators for chemical polymer degradation detectable but in the low temperature region of the first melting curve (physical effects e.g. crystallinity, orientation..)

TD / GC-MS analysis of EVA

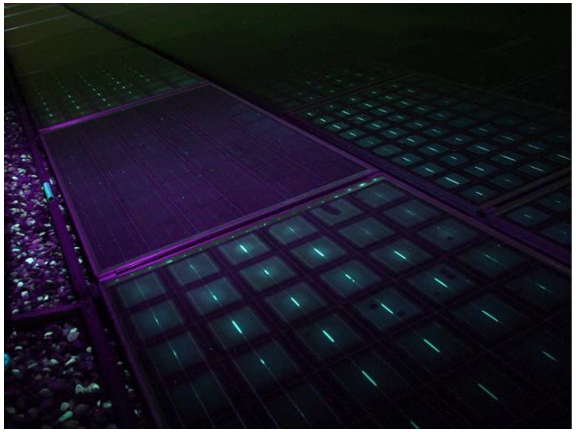
No differences in additive concentration or degradation products detectable

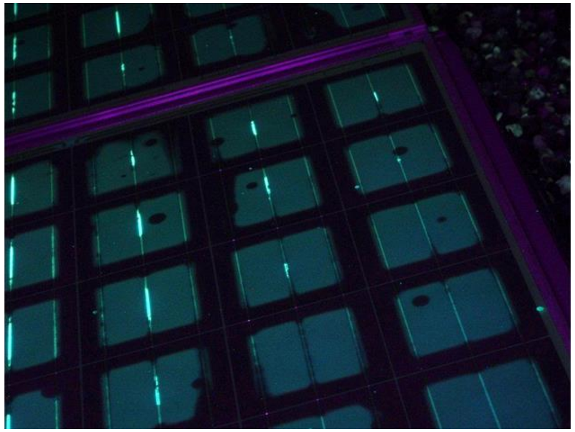
Extinction of Fuorescence

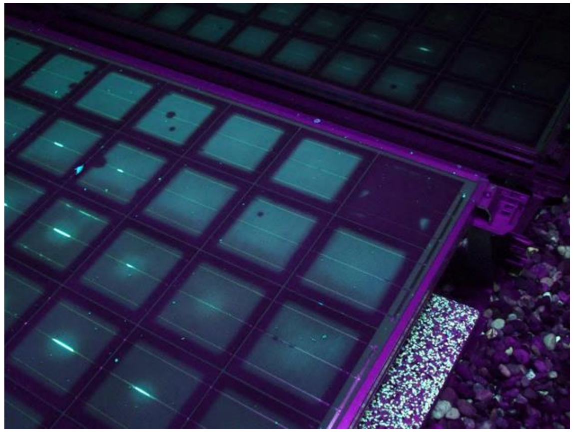
Quenching: decrease of fluorescence intensity of a given substance caused by e.g. energy transfer, complex-formation or collisions. Typical quencher: oxygen (reversible)

(Photo)-Bleaching: decrease of fluorescence intensity due to (photo)-chemical alteration of the fluorophore e.g. by cleaving of covalent bonds with surrounding molecules (permanent)

→ extinction at the rims of the cells increases with module age; extinction above cell-cracks







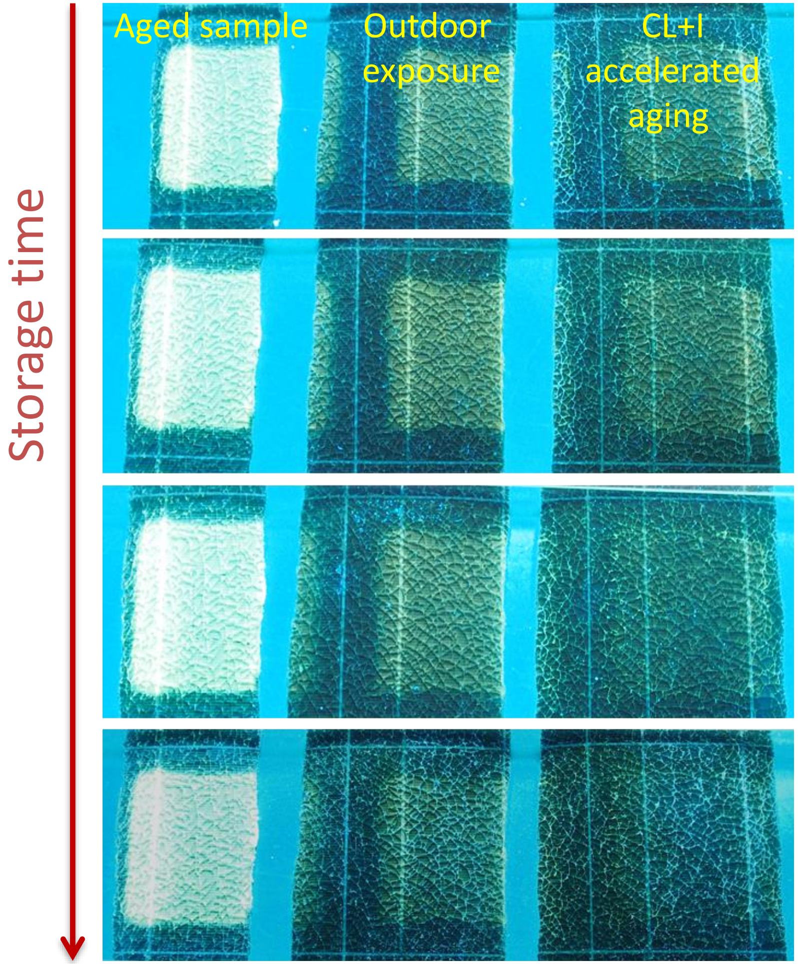
Fluorescence extinction

Fluorescence is extinct in the presence of oxygen AND irradiation

Photo-bleaching

Polymer is chemically altered = degradation

Temperature accelerates the process



Modell for the extinction of fluorescence

1. After outdoor weathering fluorescence effects are observed in the encapsulation of PV-module

2. With increasing exposure time, the polymer ages (formation of activated sites; excited-state structure) due to the influence of various stress factors and operation conditions -> fluorescence effects are observed

3. The fluorescence of materials can be extinguished by “quenching”-effects which lead to a decrease of fluorescence at the rims of the cells due to non-radiating processes like collision/energy transfer with e.g. permeating oxygen; the polymer is chemically not altered.

4. An extinction of strong fluorescence above the cells can be achieved in the presence of oxygen AND irradiation. Elevated temperatures accelerate the process (photo-bleaching). The resulting polymer has modified polymer chain structure which leads to different thermo-mechanical properties.

Influence factors on the fluorescence pattern

…apart from stress factors applied ……

Barrier-properties of the backsheet

- Oxygen, Water Vapour ,…-> quenching and bleaching effects
- Glass / breathable↔ high barrier polymeric composite BS

Type and composition of the encapsulant

- Additives
- Aeging/degradation effects (hydrolysis, photo-oxidation..)

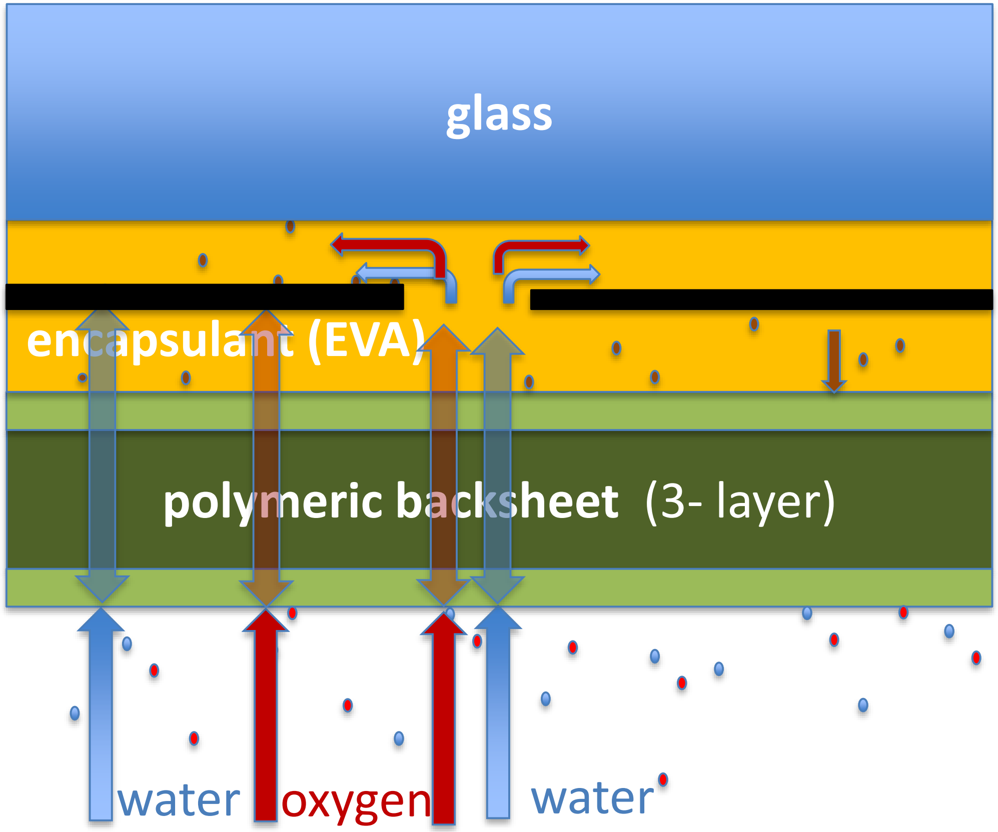
Glued (ECA) ↔ soldered ribbons

- Fluorescing components of ECA → permeation
- Material incompatibilities

Influence of barrier properties on fluorescence pattern

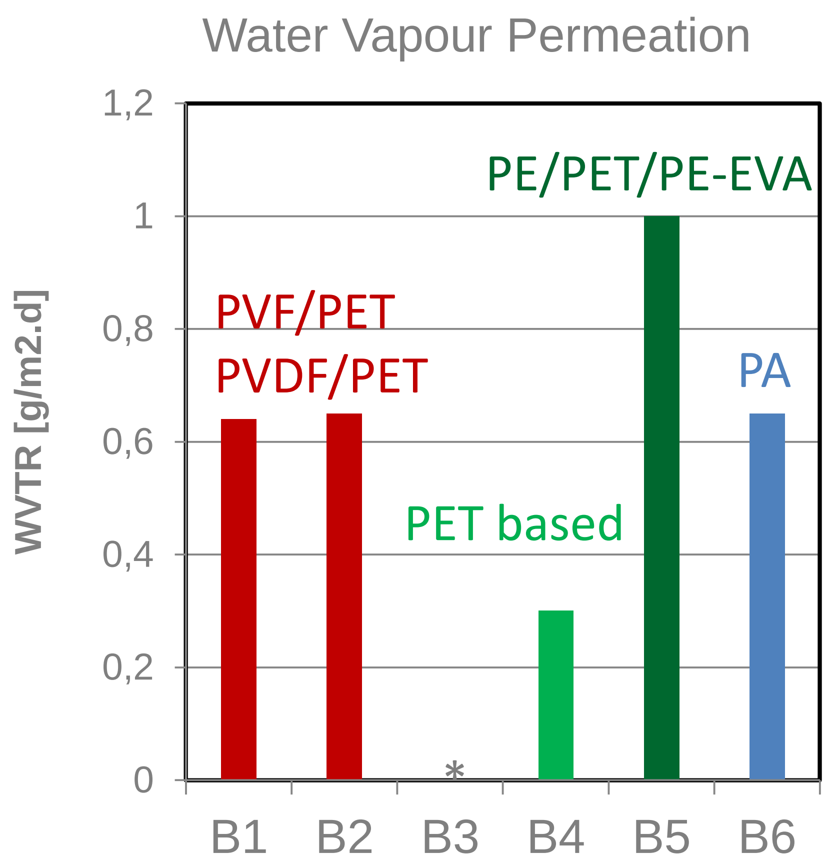
Gas-permeable backsheet

- oxygen
- water vapour
- decomposition products e.g. EVA: acetic acid

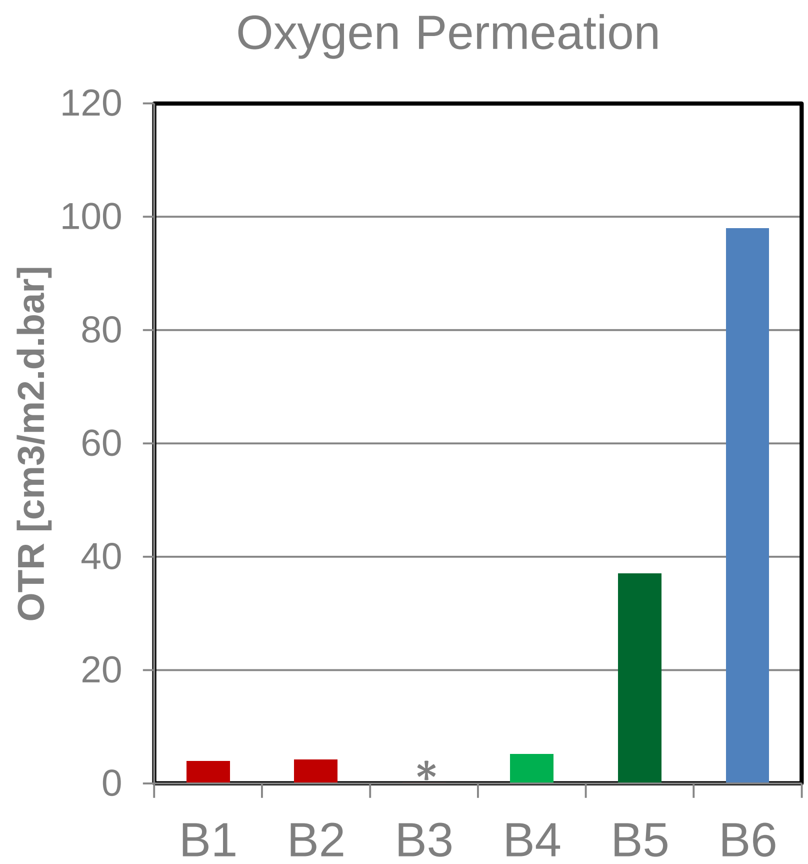


- **Oxygen** and other molecules permeating into the front encapsulant via a permeable backsheet can **quench/bleach the fluorescence** in the interspaces between the cells and above cell cracks → specific fluorescence pattern
- the extent of fluorescence extinction is dependent on OTR of the backsheet and the encapsulant and the exposure time

Permeation Properties of Backsheets



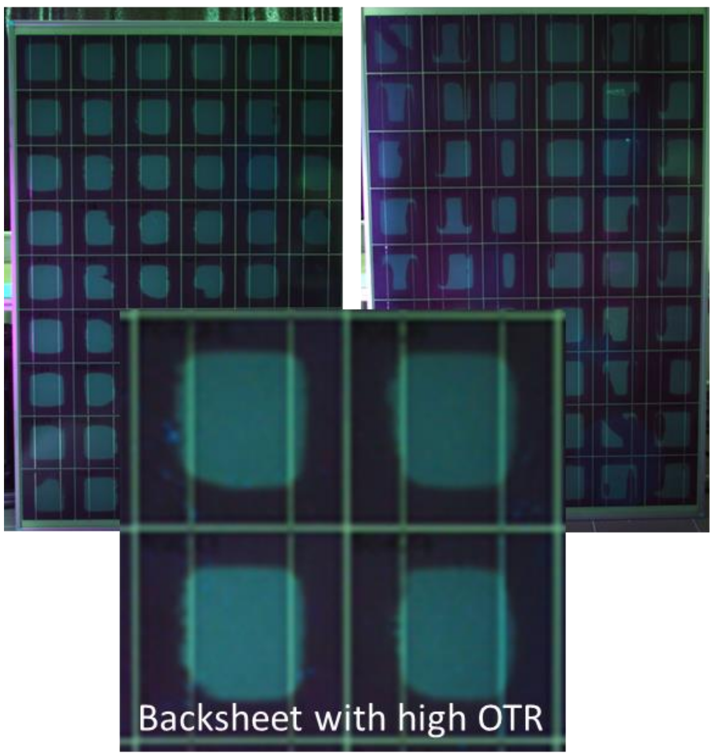
* below limit of detection < 0,1g/m2.d

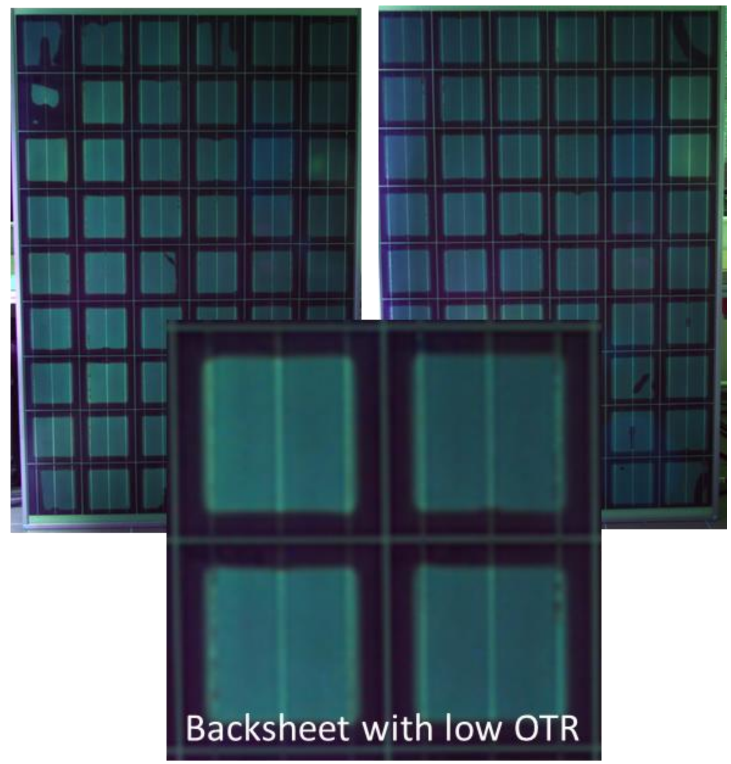


O_2 is important in fluoresence extinction

Effect of type of Backsheet on UV-F pattern

Fluorescence pattern of naturally aged (~5 years, same plant) PV modules with different backsheets





The OTR through the backsheet into the encapsulation determines the extent of the “extinction of the fluorescence”= **Oxygen-bleaching**;

→ broad rims with no fluorescence (extinguished) around the cells;

→ cell-cracks become visible

Differences in the UV-F Pattern

Besides the **type of backsheet (barrier-properties)** also **different qualities/types of encapsulant** can cause varying fluorescence effects

- the **polymer-type**
- **impurities**
- **crosslinker** and its decomposition products
- **additives** (and their degradation products)

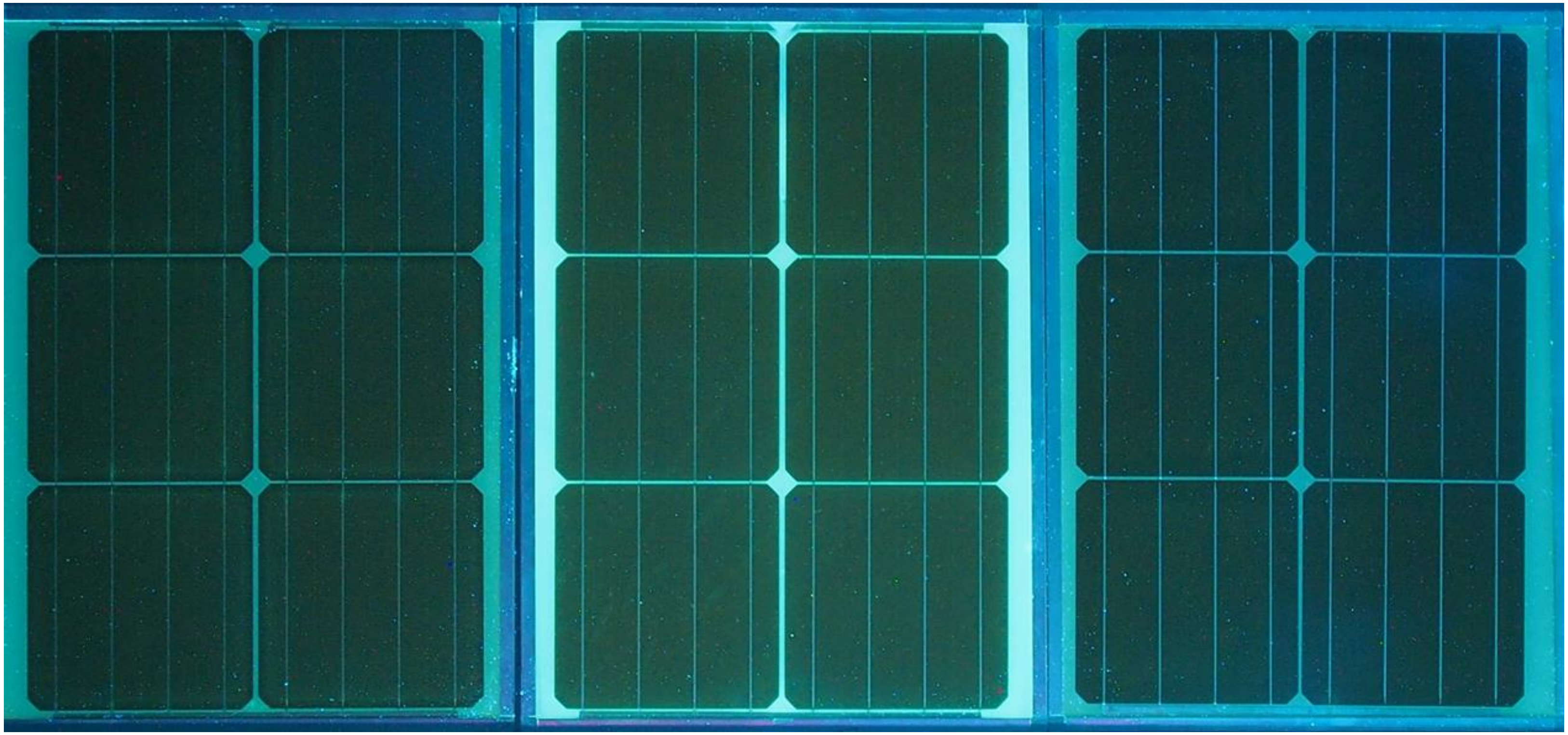
can show fluorescence*.

* C. Peike et al, “Towards the origin of photochemical EVA discoloration”, Proceedings of the IEEE · June 2013; DOI: 10.1109/PVSC.2013.6744447

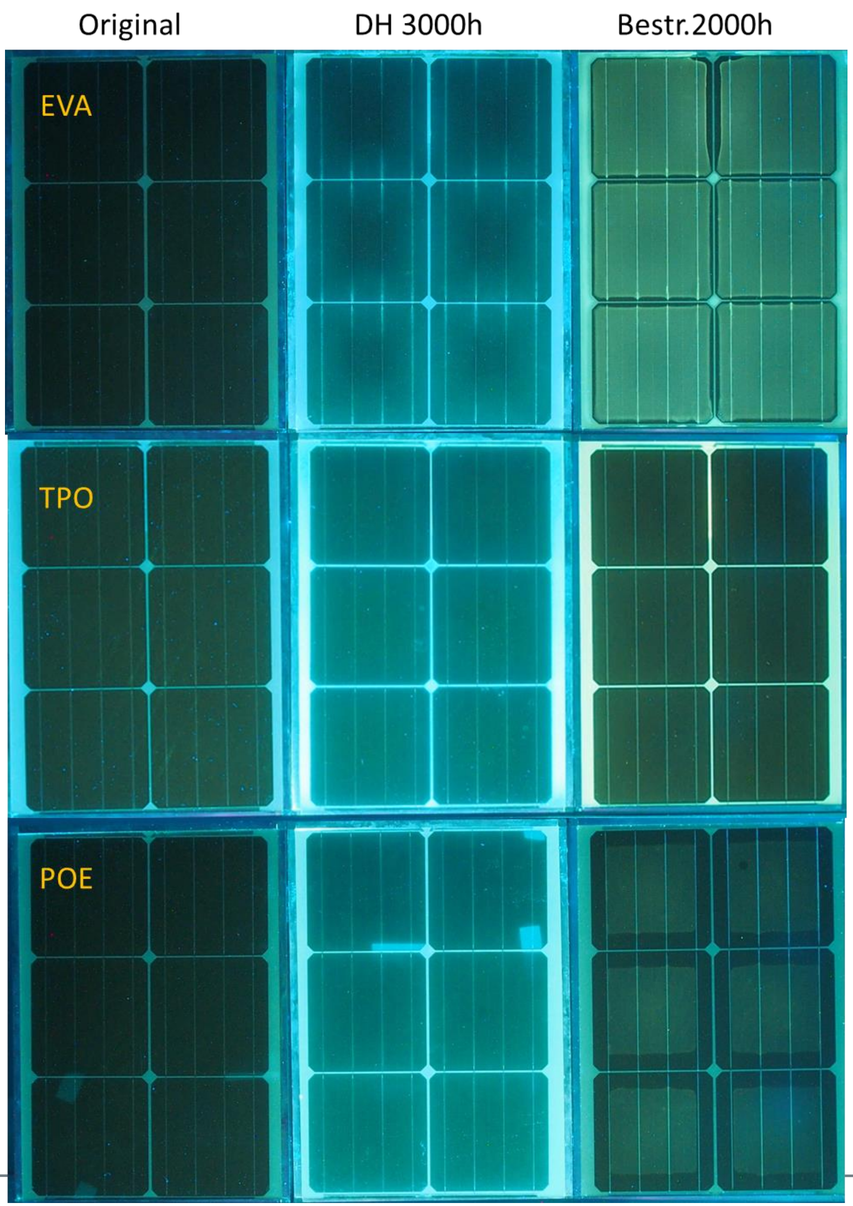
UV-F of different native encapsulants

Identical backsheet
varying encapsulation

EVA TPO POE (crosslinked)



Effect of the type of encapsulant on the fluoresence



Identical backsheet varying encapsulation

EVA / Peroxidic crosslinker, AO, UVA-Absorber

TPO / no crosslinker, no additives in front-layer

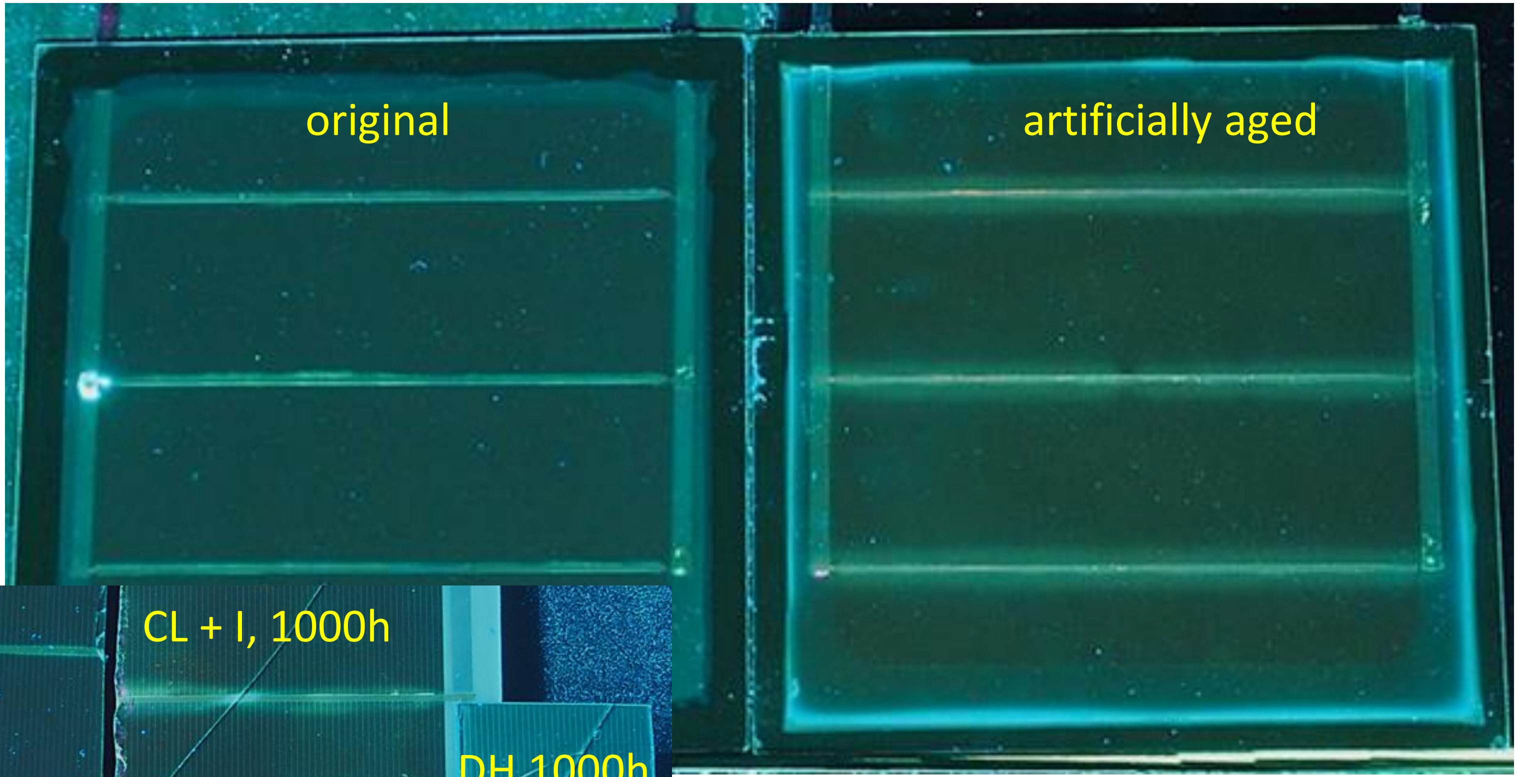
POE / chemical crosslinker

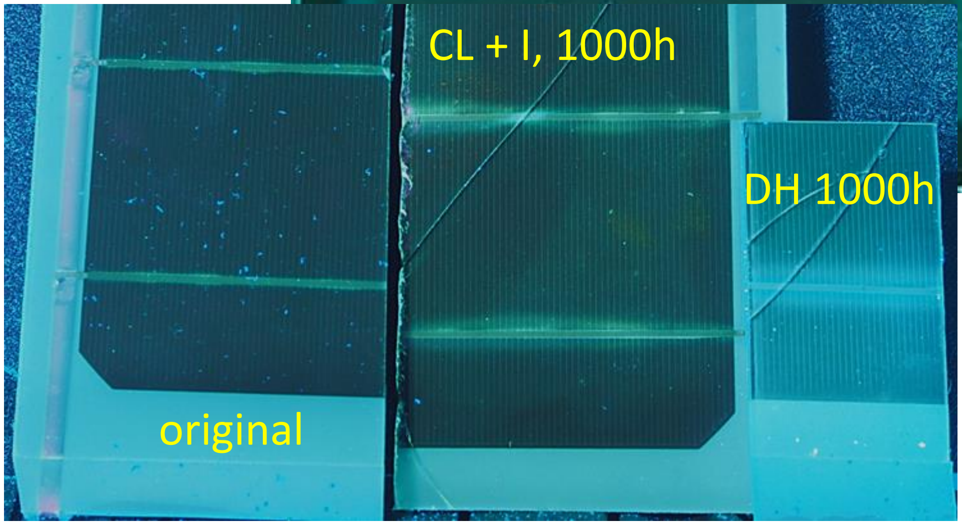
Fluorescence of polymeric encapsulants

In general, the polymeric encapsulate of PV modules does not show distinctive fluorescence effects in the original state. This holds true for the polymer itself, however, special constituents (impurities, additives or fragments of a cross linker) exhibit some weak effects which mostly depend on the exact encapsulant formulation.

With increasing lifetime, the encapsulant material ages due to the interaction with climatic stress factors (mainly irradiation by sunlight and elevated temperature) by forming fluorophores. The fluorescing effect is increasing with exposure time and is typically observable for PV-modules in operation in the field for more than a year.

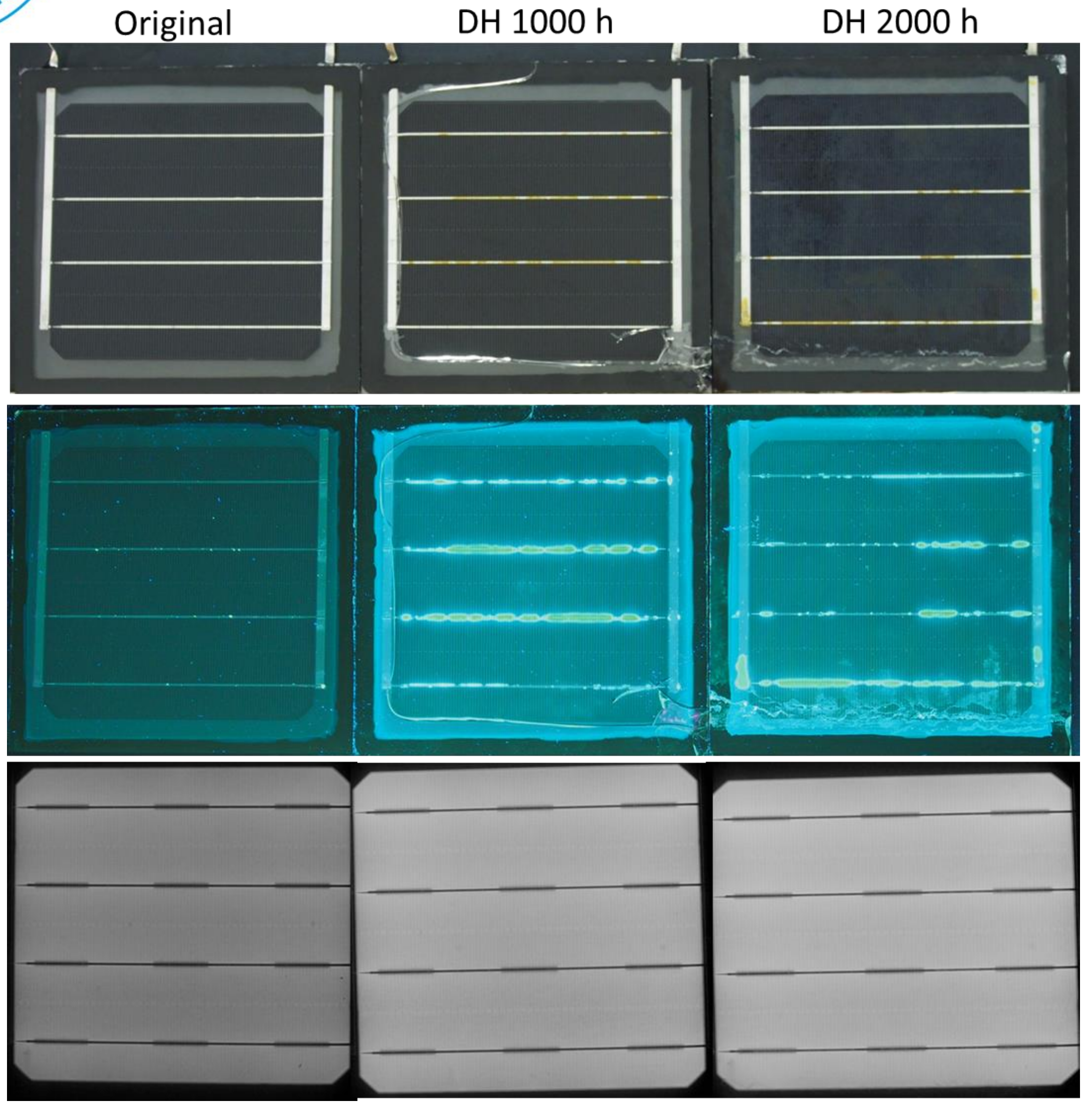
Example: Visulaisation of compound migration





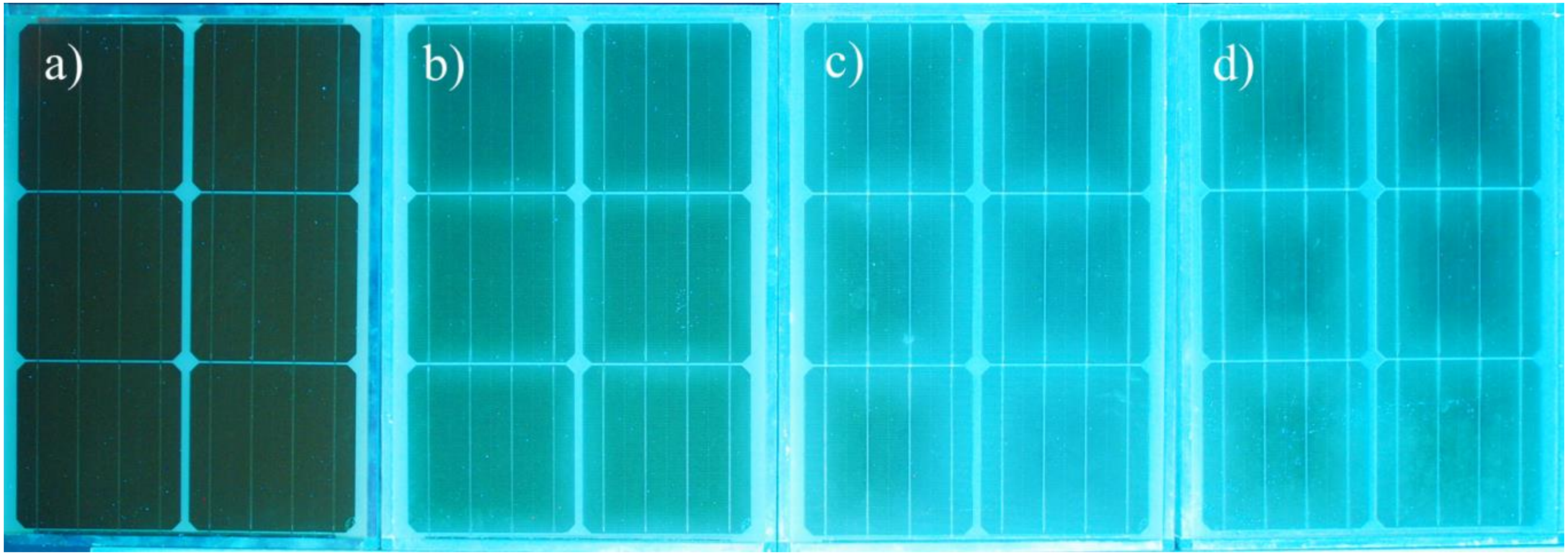
Visualisation of hardener migration
Electrically Conductive Adhesive (ECA)
in combination with Cu- or Ag-ribbons

Example: visualisation of material incompatibility



TPO
Glas/ Glass Modules
Solder Sn/Pb

Example: visualisation of water vapour ingress



UV-Fluorescence images of test modules
(a) in the original state,
(b) after 1000h
(c) after 2000h
(d) after 3000h
of exposure to DH at 85°C/85% r.H.
→ **visualisation of water ingress / hydrolysis of EVA**

Summary: Influence on fluorescence

It was found that the **fluorescence image patterns** obtained for the naturally and/or artificially aged modules depend

(i) on the composition of the PV-module; in particular if gas-tight (glass, backsheets with Al-barrier layers) or breathable (polymeric backsheets) are used (Oxygen Quenching)

(ii) If cell-cracks, pinholes in the cell or hot cells are present (Oxygen Q.)

(iii) on the stress factors applied

The fluorescence spectra (intensity, maxima) depend

(ii) the type of encapsulant used – especially on the additive mixture and peroxidic curing system used

(iii) on the stress factors (temperature, humidity, irradiation, ….) applied at the installation site or in the climatic chamber in accelerated ageing tests

Thank you for your attention !

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