Solution Series 14

Exercise 1: Tandem cells

Consider two solar cells in tandem, a and b, that are not interconnected monolithically (two terminals for the whole stack of the two cells) but as a 4-terminal (two terminals for each cell, so four in total) tandem device, such that the *I*-*V* curves of each cell could be measured independently of the other one:

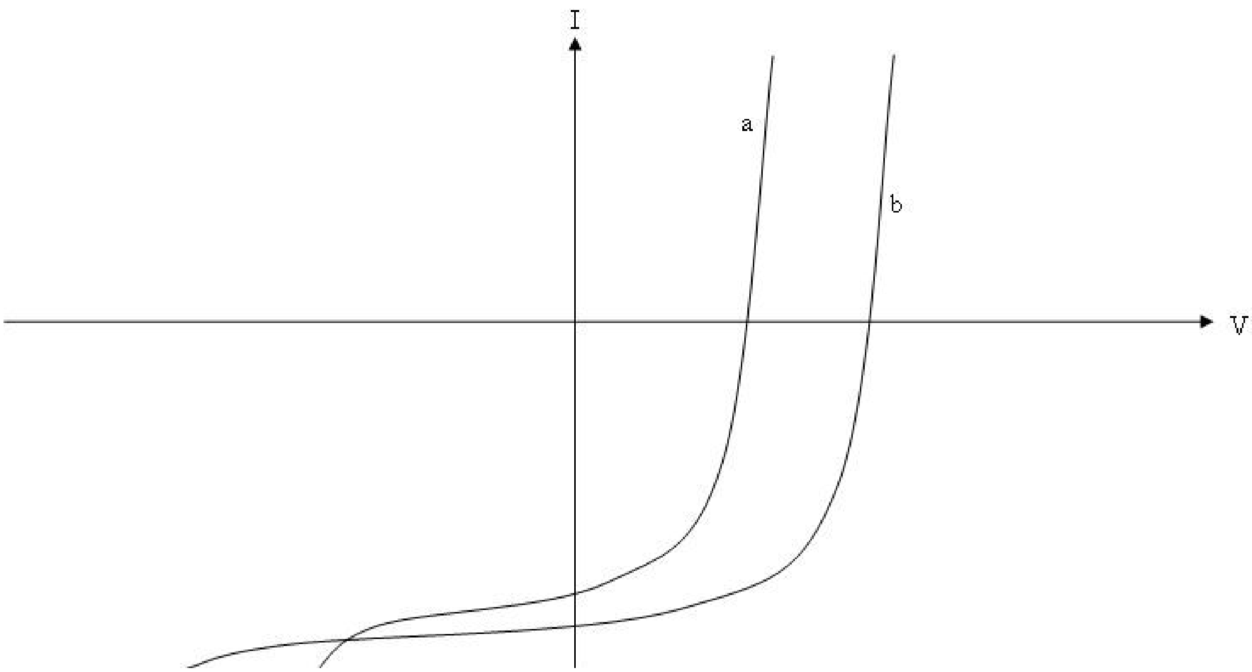


Figure 1: *I*-*V* curves of two solar cells a and b that are used together in a tandem device.

a) Which cell is the top/bottom cell and why?

Solution:

Semiconductors absorb photons with energy $E_{photon} > E_g$ and transmit photons with $E_{photon} < E_g$. Therefore the lowest E_g subcell should always be placed below the others, to not parasitically absorb high energy photons before reaching the other cell. This allows the larger bandgap cell - which is sensitive in the blue range - to pass enough red light to be absorbed in the bottom cell. From the rule of thumb $V_{oc} \approx \frac{2}{3}E_g$ it is clear, that cell 'a' has a smaller bandgap than cell 'b'. Therefore, it is used as the bottom cell and cell 'b' as the top cell.

Imagine now that you interconnect the two cells monolithically.

b) Draw the *I*-*V* curves of the cell [ab] (or [ba] according to your answer a)).

Solution:

To interconnect the cells b and a monolithically means to connect them in series. Therefore, the same current flow in the whole device, and for each given current I, the corresponding voltages Va and Vb are added, resulting in the following *I*-*V* curve:

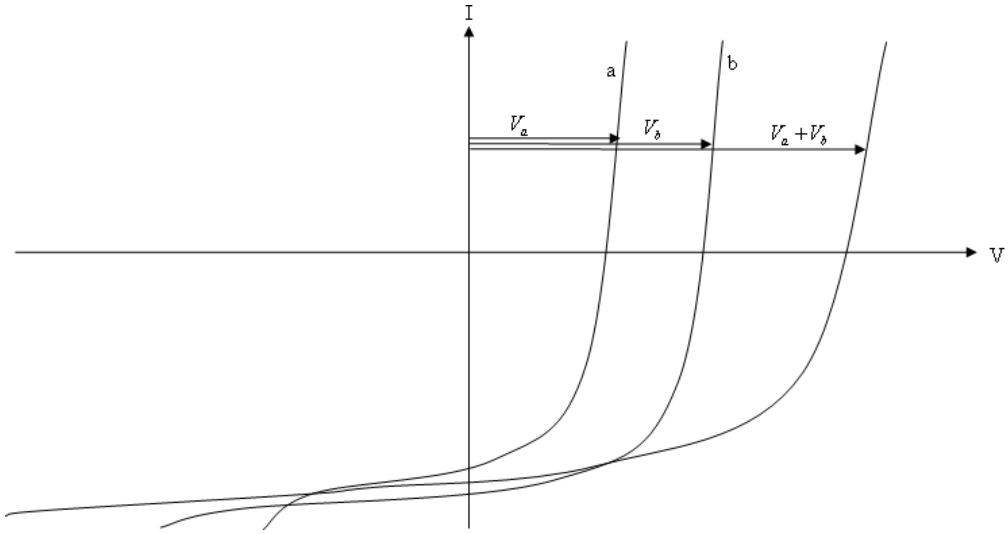


Figure 2: I-V curves of two solar cells a and b and the curve of the monolithically interconnected cell ba.

c) Which cell is the limiting one and why?

Solution:

The current at the maximum power point (MPP) is relevant for which cell is the limiting one. From the plot, one can see that $I^{\mathrm{a}}_{\mathrm{MPP}} < I^{\mathrm{b}}_{\mathrm{MPP}}$, therefore cell 'a' is the limiting cell and the tandem cell 'ba' is bottom-limited.

Additional readings on new tandem devices:
III-V on Silicon: IEEE JPV, 2016.
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7460224
Perovskite on Silicon: JPCL 2016, 7.
http://pubs.acs.org/doi/abs/10.1021/acs.jpclett.5b02686

Exercise 2: Thin Film module

By building not only small test cells but whole modules, one interconnects stripes of solar cells in series by laser scribe as shown in figure 3.

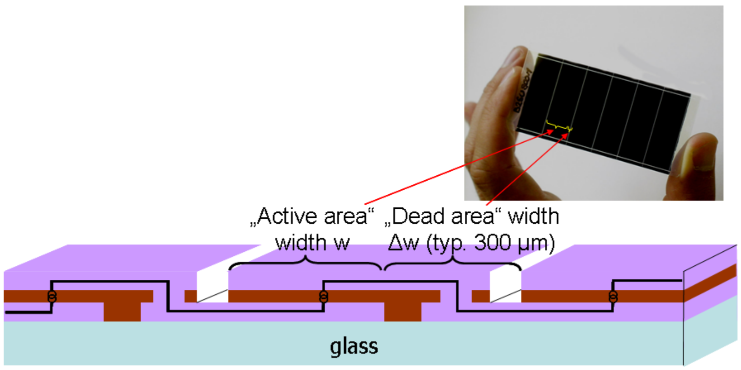


Figure 3: : Single solar cell stripes interconnected in series by laser scribe.

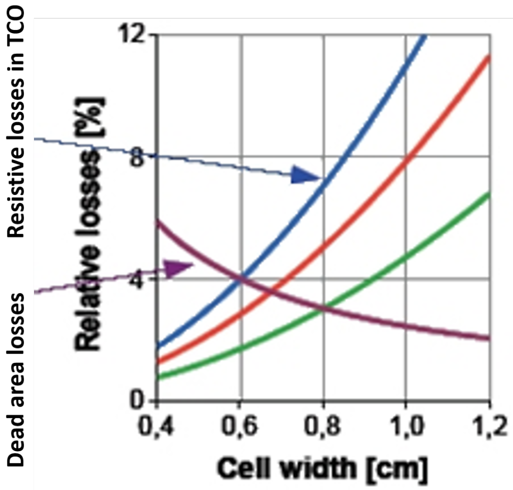


Figure 4: : Larger cells have higher serial resistancies in the TCO, but less dead material.

a) Why is it recommended to separate a module into several smaller stripes?

Solution:

If a whole module acts as a single cell, the current reaches astronomical values towards the terminals resulting in huge power losses due to resistivity of the TCO. Separating a module into smaller cells that are interconnected in series reduces drastically the mean current.

b) Two opposite effects lead to an optimum width w for given Δw as can be seen in figure 4: On one hand, the laser scribe region Δw is 'dead' material, i.e. no current is produced there. Thus, the wider the cell is (large width w), the lower the relative losses due to the dead area Δw. On the other hand, too large stripes (large width w) lead to a drop of efficiency due to serial resistivity of the TCO.
Find the analytical formula for $w(\eta_{\max})$.
The following approach is recommended:

- Calculate the relative power loss $\frac{\Delta p_{\mathrm{i}}}{p}$ due to dead zones.
- Calculate the relative power loss $\frac{\Delta p_{\mathrm{ii}}}{p}$ due to the series resistance introduced by the top-TCO. Therefore, calculate first the current at each position of a cell, then the mean current square in a cell, and finally the power loss. Consider hereby the sheet resistance R_{sheet} with $R_{\mathrm{s}} = R_{sheet} \cdot \frac{\Delta x}{\Delta y}$ the resistance for a layer of width Δy and a length Δx (current flows in x direction) and where R_{s} is the series resistance.
- Minimize the sum of the power losses.

Solution:

The effect (i) of introducing 'dead' zones due to laser scribe is simply described by a relative power loss due to lost active area:

$$\frac{\Delta p_{\mathrm{i}}}{p} = \frac{\Delta w}{w + \Delta w}. \tag{1}$$

A little bit trickier to calculate is the power loss (ii) due to the resistance of the TCO. We assume that only the upper TCO adds a serial resistance R_{s} that depends on the sheet resistance $R_{\square}$ in $[\frac{\Omega}{\square}]$, "Ohm square", in the following way:

$$R_{\mathrm{s}} = R_{\square} \cdot \frac{nw}{l}, \tag{2}$$

with l the length of a module and n the number of stripes

The current in the TCO leading to a drop of voltage and power is not constant over the cell, therefore one has to take an average value:

$$\begin{aligned}
\Delta p_{\mathrm{ii}} &= \overline{\Delta V \cdot I}^{\text{module}} && (3)\\
&= R_{\mathrm{s}} \cdot \overline{I^2}^{\text{module}} && (4)\\
&= R_{\square} \cdot \frac{nw}{l} \cdot \overline{I^2}^{\text{module}} && (5)\\
&= R_{\square} \cdot \frac{nw}{l} \cdot \overline{I^2}^{\text{cell}} && (6)\\
&\overset{(*)}{=} R_{\square} \cdot \frac{nw}{l} \cdot \frac{1}{3} \cdot (l \cdot w \cdot J)^2 && (7)\\
&= \frac{1}{3} \cdot R_{\square} \cdot n \cdot l \cdot w^3 \cdot J^2. && (8)
\end{aligned}$$

Before taking the average of I^2 over a cell in $(*)$, one determines first the current at each position x in the TCO above the cell:

$$\begin{aligned}
\overline{I^2}^{\text{cell}} &= \overline{\left(\int_0^x \int_0^l J \, \mathrm{d}l' \, \mathrm{d}x'\right)^2}^{\text{cell}} && (9)\\
&= \overline{(x \cdot l \cdot J)^2}^{\text{cell}} && (10)\\
&= \frac{1}{w} \int_0^w (x \cdot l \cdot J)^2 \, \mathrm{d}x' && (11)\\
&= \frac{1}{w} \left[\frac{1}{3} \cdot l^2 \cdot J^2 \cdot x^3\right]_0^w && (12)\\
&= \frac{1}{3} \cdot l^2 \cdot J^2 \cdot w^2. && (13)
\end{aligned}$$

Further it is:

$$\begin{aligned}
p &= n \cdot V \cdot I && (14)\\
&= n \cdot V \cdot l \cdot w \cdot J && (15)
\end{aligned}$$

and therefore

$$\frac{\Delta p_{\text{ii}}}{p} = \frac{\frac{1}{3} \cdot R_{\square} \cdot n \cdot l \cdot w^3 \cdot J^2}{n \cdot V \cdot l \cdot w \cdot J} \tag{16}$$

$$= \frac{R_{\square} \cdot w^2 \cdot J}{3 \cdot V}. \tag{17}$$

To minimize $\frac{\Delta p}{p} = \frac{\Delta p_{\text{i}}}{p} + \frac{\Delta p_{\text{ii}}}{p}$ with respect to w, we say:

$$0 \stackrel{!}{=} \frac{\partial}{\partial w} \frac{\Delta p}{p} \tag{18}$$

$$= \frac{\partial}{\partial w} \left[\frac{\Delta w}{w + \Delta w} + \frac{R_{\square} \cdot w^2 \cdot J}{3 \cdot V} \right] \tag{19}$$

$$= \frac{-\Delta w}{(w + \Delta w)^2} + \frac{2 \cdot R_{\square} \cdot w \cdot J}{3 \cdot V} \tag{20}$$

This last equation is a polynomial of 3^{rd} degree which is solvable only numerically with concrete values for Δw, J, $R_{\square}$ and V. Taking for example 300 μm, 78 $\frac{A}{m^2}$, 10 $\Omega/\square$ and 0.94 V respectively for these variables[1], we get an optimal width w of 0.8 cm.

Solution:

Even without solving equation (20) numerically, one can say that μc-Si:H modules should have smaller cells than a-Si:H modules: Assuming same $R_{\square}$ and Δw, only differences of V and I in the term $\frac{\Delta p_{\text{ii}}}{p}$ can shift the minimum of $\frac{\Delta p}{p}$ towards larger/smaller w. μc-Si:H cells have smaller V_{mpp} and larger I_{mpp} than a-Si:H cells; Both effects lead to an increase of $\frac{\Delta p_{\text{ii}}}{p}$ and with it to a smaller optimum w.
Practically, μc-Si:H cells are used only together with a-Si:H cells as tandem devices: As single cells, they have about the same efficiency as a-Si:H cells, but by far higher production costs due to the larger thickness.

Exercise 3: Solar Cell technologies

In this exercise, we review 9 different semiconductor solar cell technologies:

a) Al-BSF cells

b) PERC solar cell

c) Interdigitaded back contacted (IBC) solar cell

d) Standard silicon heterojunction (SHJ, or "HIT" for Heterojunction with Intrinsic Thin film) as Sanyo trademark) solar cell

[1] estimated values for U-EA120, http://www.kaneka-solar.com/product/thin-film/pdf/U-EA.pdf, consulted on 11.06.2018

e) Perovskite solar cell

For each technology,

- draw the solar cell structure (layer stack, materials and typical thickness for each layer),
- draw the band diagram
- mention the advantages and drawback of each technology,
- state the efficiencies of these cells on lab scale and for a typical module (if available).

Solution:

Note that the answers given here summarize only a few key points and are not considered to be an exhaustive description.

c-Si technologies

a) Conventional diffused junction c-Si solar cell

Silicon is an abundant element and wafer preparation is well known. The standard technology has proven its feasibility and reliability. However, c-Si wafers are expensive and large thickness is needed (200 µm).
Typical parameters: V_{oc} of 600 - 650 mV; J_{sc} of 30 mA cm^{-2}; $S = 10^7$ cm s^{-1}
Cell process flow should be known, from sand to finished cell and module.

b) PERC solar cell

PERL = Passivated Emitter and Rear Cell. The main difference between the PERL cell and the Al-BSF is the higher rear passivation and metallic contact partial isolation from the cell active area (bulk+emitter). This is achieved by adding an AlOx/SiNx stack on the rear side, which is locally opened to allow for direct Al-Si contact only locally under the openings.
Typical parameters: V_{oc} of 680 - 690 mV; J_{sc} of 40 mA cm^{-2};

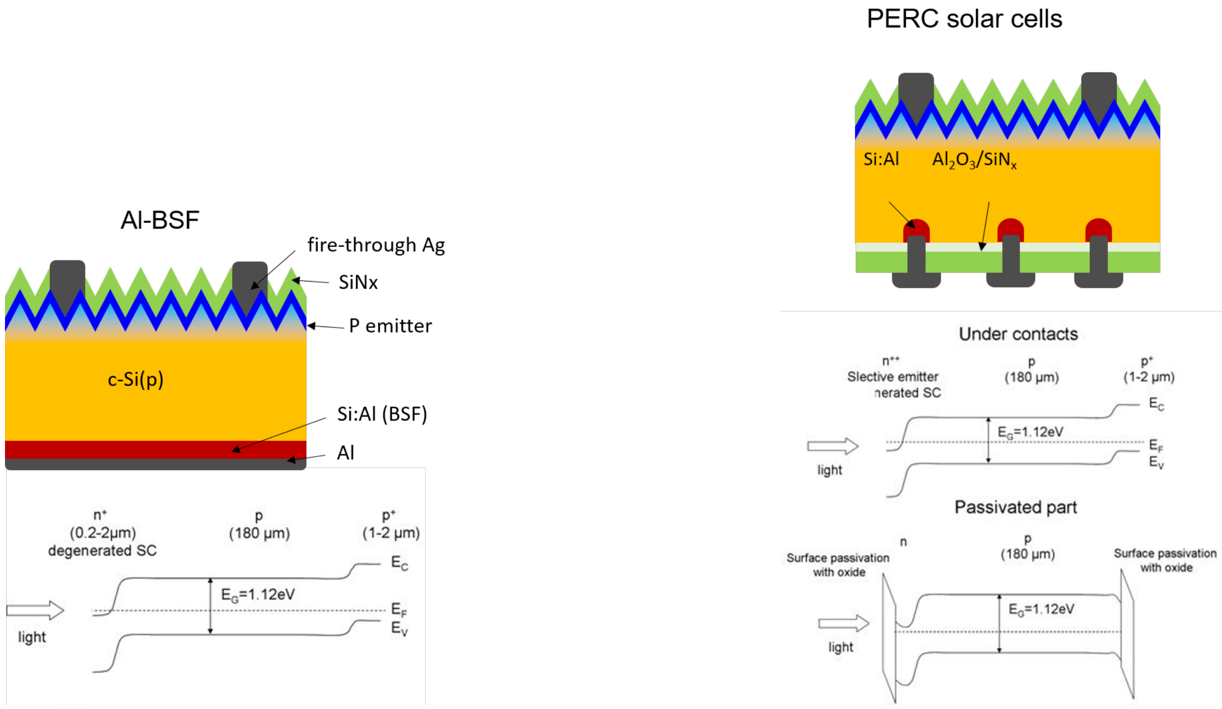
PERC cells represent the mainstream in the market nowadays. Full cell process flow should be known, as well as typical parameters (e.g efficiency, Voc, wafer thickness, emitter doping and depth etc...)

c) Interdigitated back contacted (IBC) solar cell

Interdigitated back contacted solar cell has the advantage of combining a high J_{sc}(>40 mA cm^{-2}) of back-contacted cells with a high V_{oc}(>700 mV) stemming from all metallic contacts at the rear side and very high passivation. However, it remains a costly process.
+: no shadowing effects therefore large J_{sc}, passivating contacts enable high V_{oc}, easier interconnection of cells
−: complex manufacturing, >30 steps (not anymore)

d) Silicon heterojunction (SHJ) solar cell

Silicon heterojunction are an elegant solution to obtain high V_{oc}(700 - 750 mV) by displacing the recombinative contacts away from the active region. It is moreover a low cost process and has a low temperature coefficient thanks to its high V_{oc}. The surface preparation of the c-Si wafers is however a stringent process.
Check the review article of S.De Wolf uploaded on the moodle.



(a) (b)

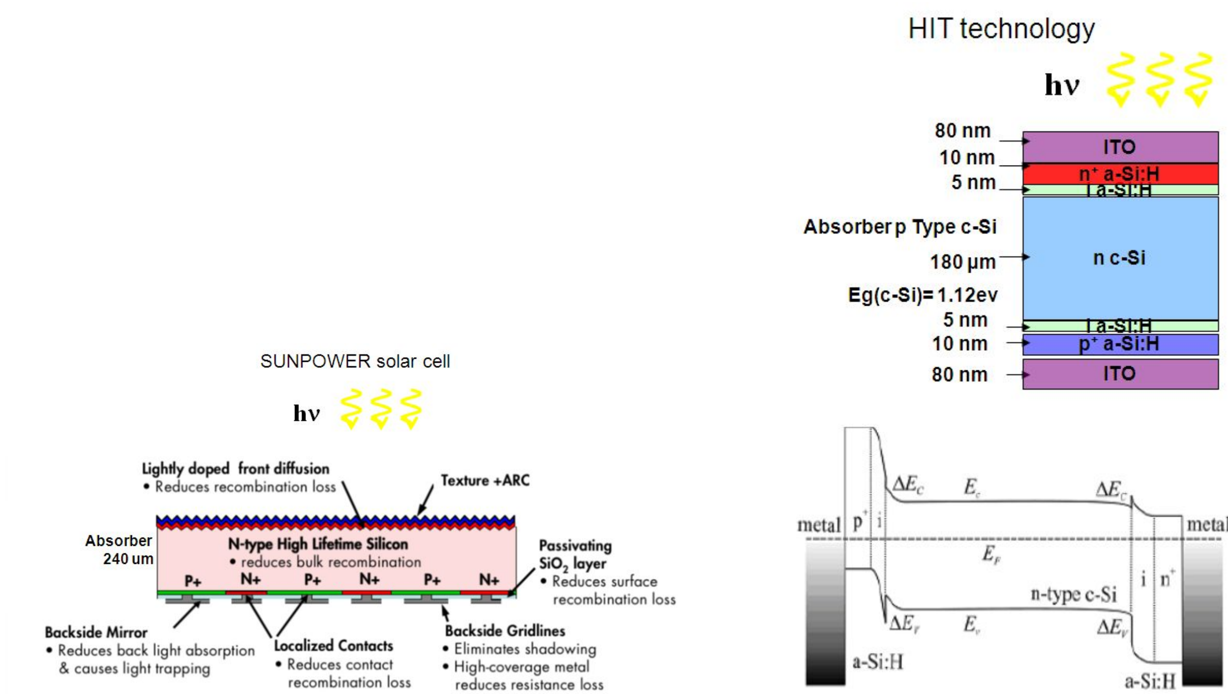
Figure 5: (a) Al-BSF solar cell. (b) PERC solar cell.

Thin film technologies

Thin films technologies represent a low cost alternative (lower amount of semiconductor material) to crystalline based technologies. Moreover, thin film panels have a good temperature coefficient, the upscaling is relatively easy and the panels are aesthetic (tunable colors). It is also possible to directly interconnect the cells during the cell fabrication process. However, the efficiencies are medium/low and due to a lack of experience in the field, reliability is more of a concern and good embedding techniques must be applied. However, they suffer from low efficiencies.

e) Perovskite solar cell

New field of research in photovoltaics, which has seen an enormous progress in just a few years: efficiency of 3.8% in 2009 and up to 25.8% in 2023. Promise for higher efficiency with low cost materials and production. It is based on a direct bandgap semiconductor having the crystal structure ABX_3 , with A = 1+ cation (methlyammonium, formamidinium, cesium), B = 2+ metal cation (Pb, Sn), and X = 1- halide anion (I, Br, Cl). The flexibility of its composition allows for diverse composition, characteristics, and processing, which enables fast research and high versatility for a semiconductor. Perovskites can be made from a wide variety of processing techniques (spin coating, ink-jet printing, slot die coating, evaporation) and different architectures are possible (mesoscopic, planar) with direct (n-i-p) or inverted (p-i-n) polarities.
Perovskites show almost ideal semiconductor properties, very similar to the III-V but with lower cost potential, large variety of deposition techniques and architectures, wide bandgap with high efficiency demonstrated, very low sub-E_g absorption makes them well suited for



(a) (b)

Figure 6: (a) Sunpower solar cell. (b) Silicon heterojuntion solar cell (here, standard SHJ, or "HIT" solar cell).

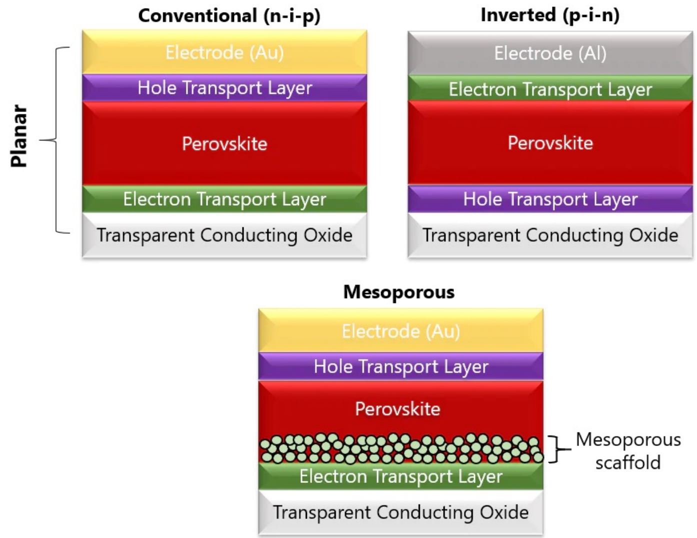


Figure 7: Perovskite solar cell: mesoscopic and planar architectures and both polarities are possible.

application as top cell in tandem devices with c-Si, showing potential for >30% efficiency at low additional costs.
Typical J_{sc} around 20-25 mA/cm^2 and V_{oc} >1.1 V for bandgap of 1.6eV, E_g tunable between 1.2 to 2eV. Stability is still problematic and is under strong investigation. Perovskites degrade into non-photoactive materials under stress from light, heat, oxygen, water vapor, and electrical biasing. From stability of minutes to now 10000 hours are demonstrated that shows the progress. Up-scaling is also in progress, many academic and industrial groups are working on this topic. Very recently perovskite/c-Si tandem on industrial M4 wafers (258.15 cm2) with certified 28.6% efficiency is demonstrated by Oxford PV.

Check out solar cell efficiencies for different technologies on: Solar cell efficiency tables (version 61), M.A. Green (available on Moodle).