Energy Conversion by Semiconductor Devices

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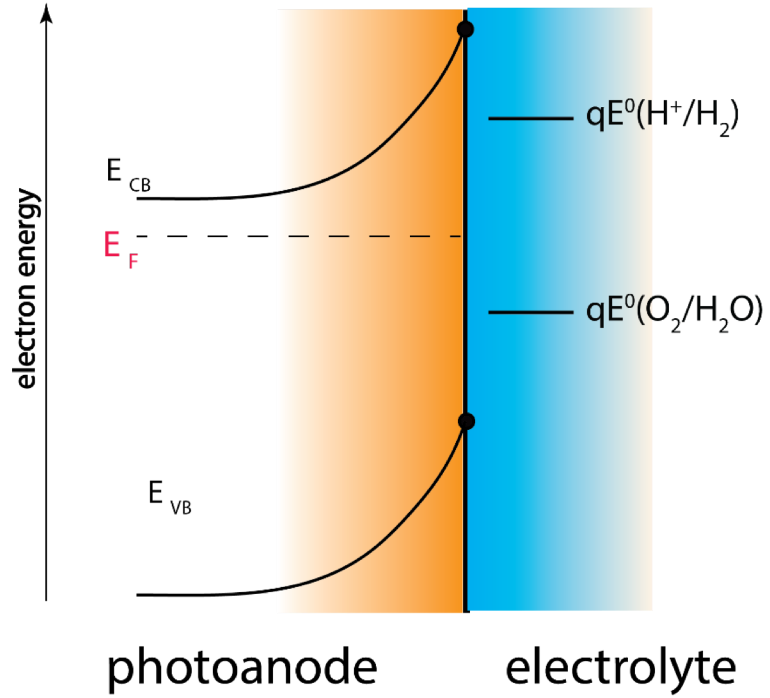
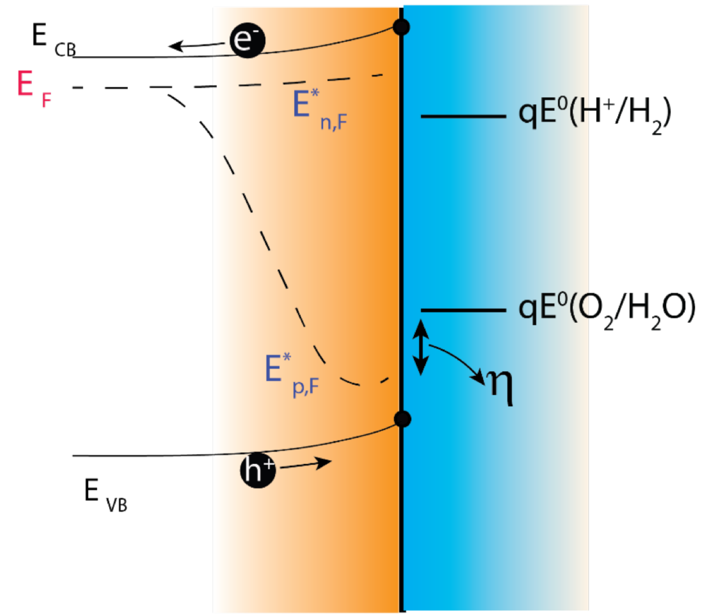
SC-Liquid Junction (SCLJ)

Dark



Light (open circuit conditions)



$$E_{n,F}^{*} = E_F + k_B T ln\left(\frac{n+\Delta n^*}{n}\right)$$

$$E_{p,F}^{*} = E_F + k_B T ln\left(\frac{p+\Delta p^*}{p}\right)$$

If n-type semiconductor

$n \gg p$

$n \gg \Delta n^*$ $\quad$ $\boldsymbol{E_{n,F}^{*} \sim E_F}$

$p = \Delta p^*$ $\quad$ $\boldsymbol{E_{p,F}^{*}}$

Photo-induced carrier concentration

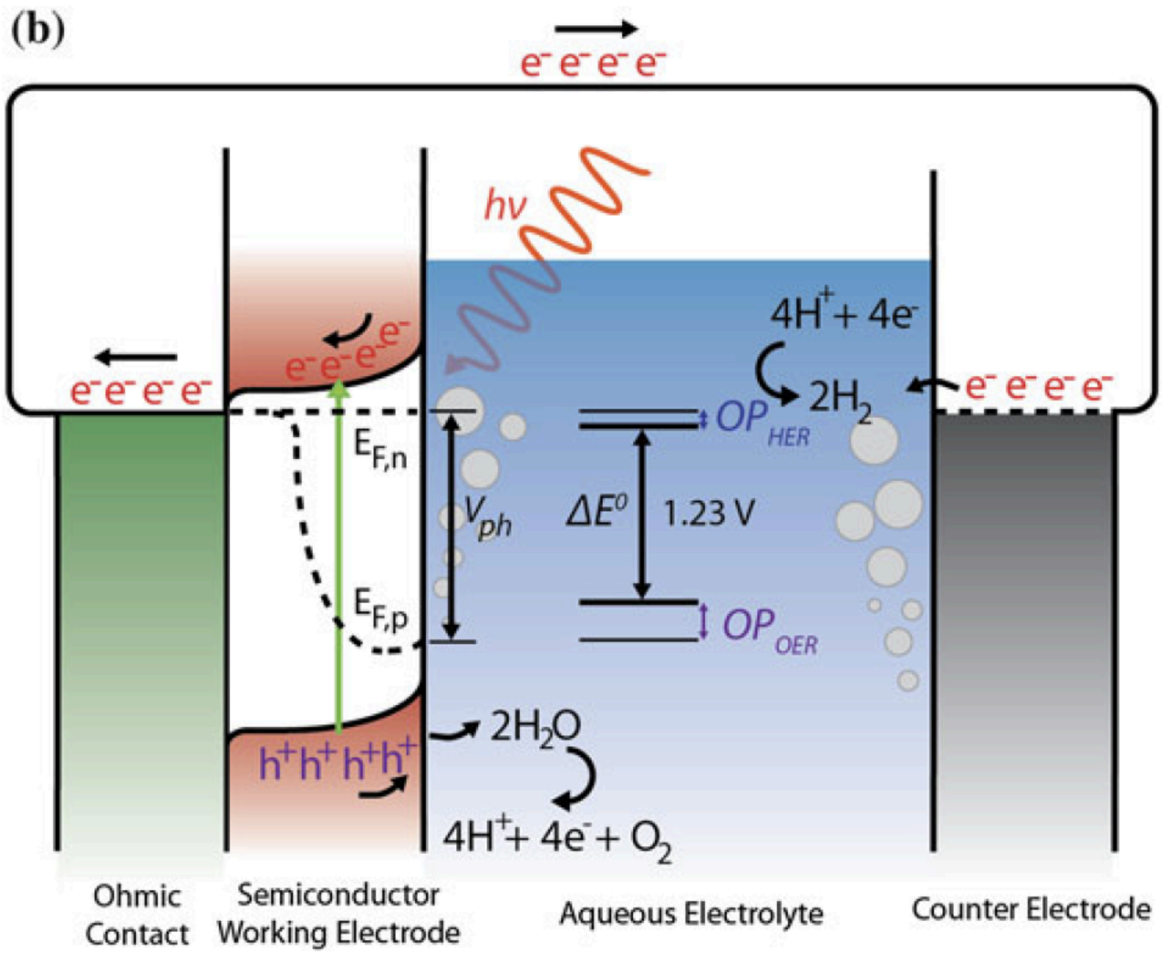
$n^* = n + \Delta n^*$

$p^* = p + \Delta p^*$

dark

Increase by light

Thermodynamic Energy to Split Water

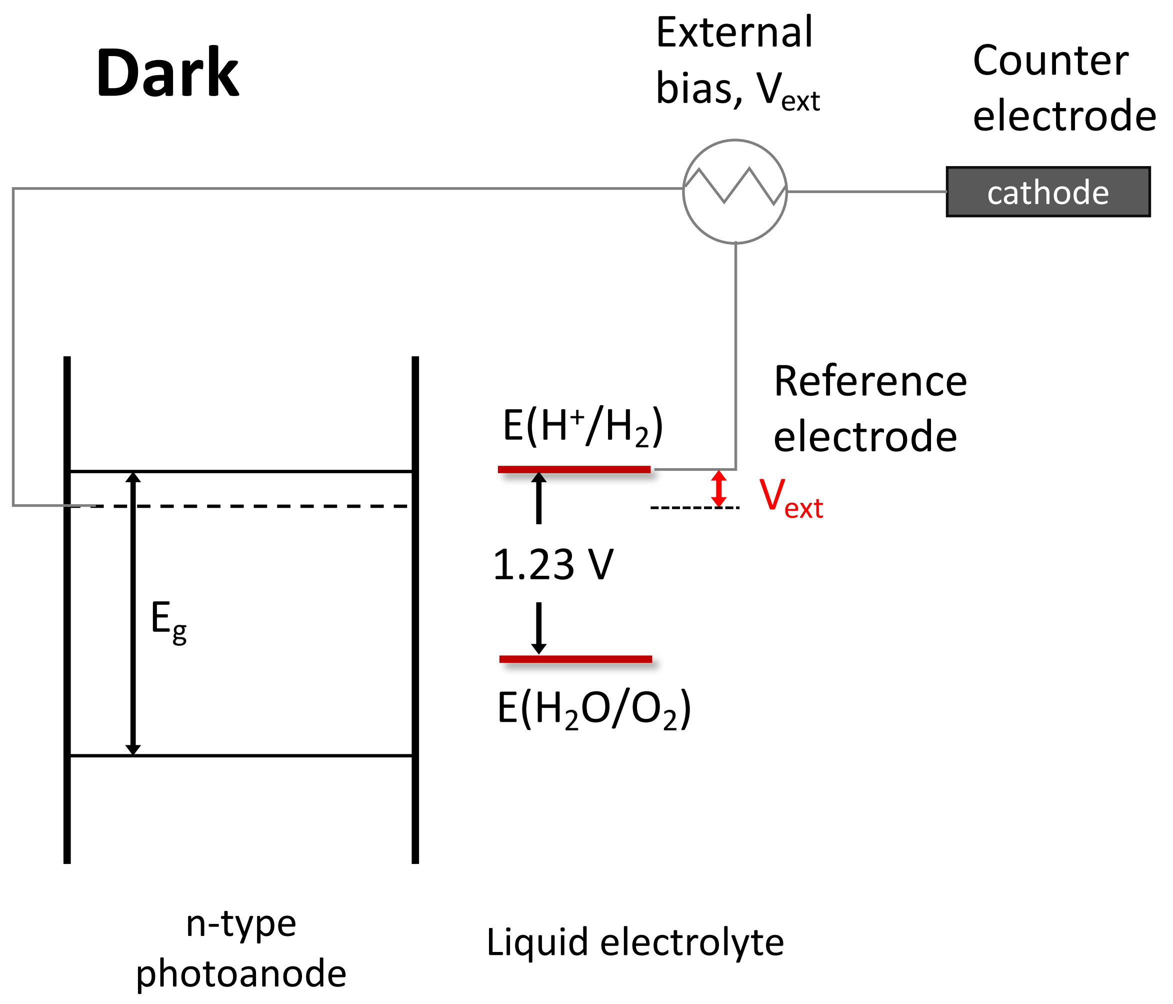


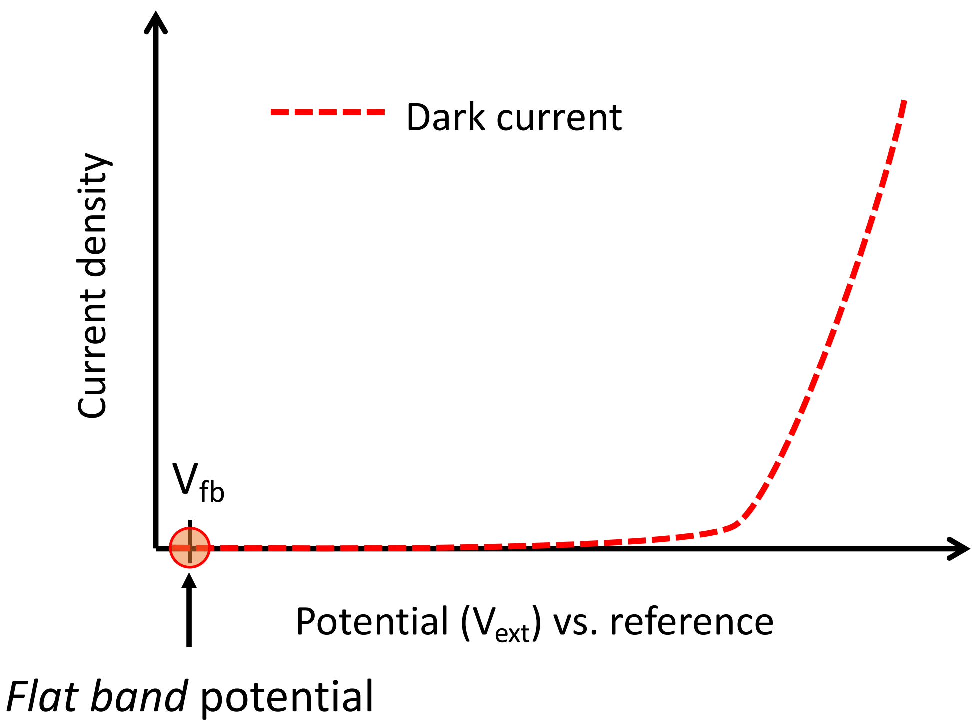
- The photovoltage in the semiconductor is **the potential difference between the quasi-Fermi levels of electrons ($E_{F,n}$) and holes ($E_{F,p}$) under illumination**.

- $\underline{V_{ph}}$ **< E_g of the SC**
  due to losses (arising from factors such as radiative recombination, incomplete light trapping, and non-radiative recombination).

- In addition to the thermodynamic requirement, there are **overpotentials associated with driving the kinetics of the HER and OER** at the solid–liquid interface.

Metrics in Photoelectrode Development

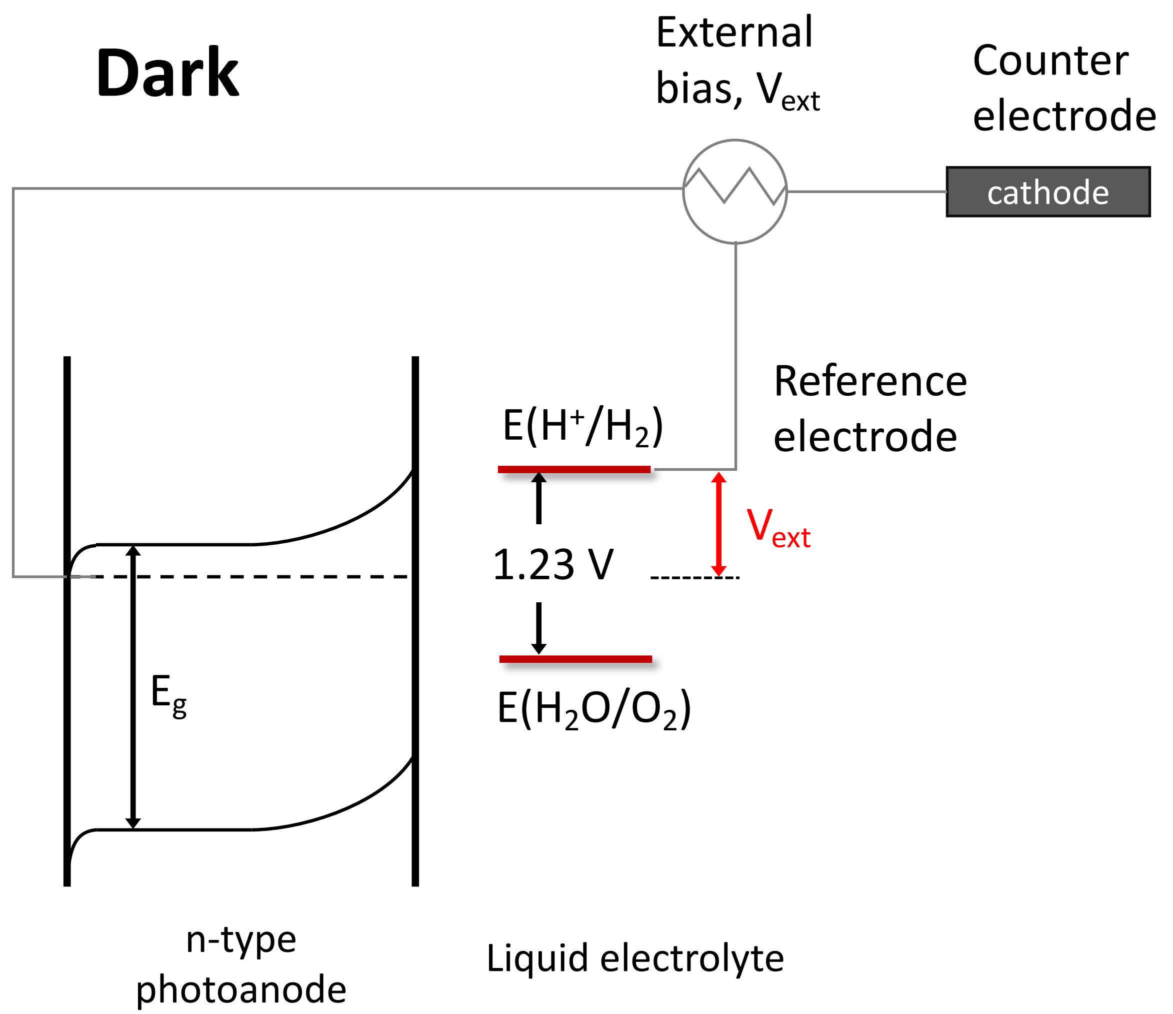


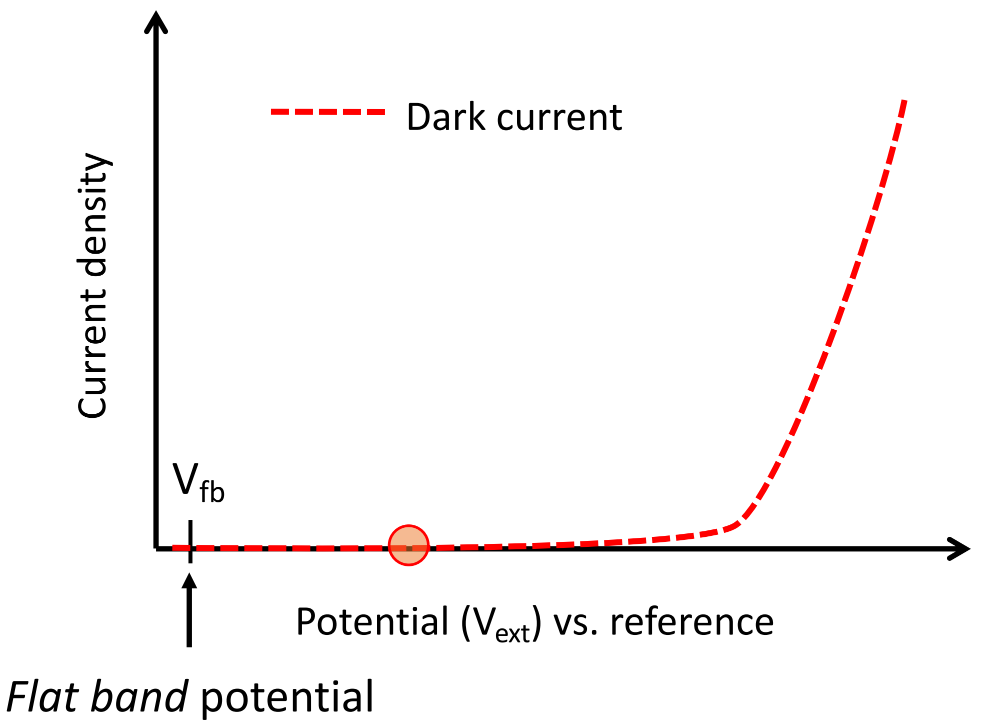


Dark current before onset should be small, indicating no irreversible processes

Metrics in Photoelectrode Development

Dark





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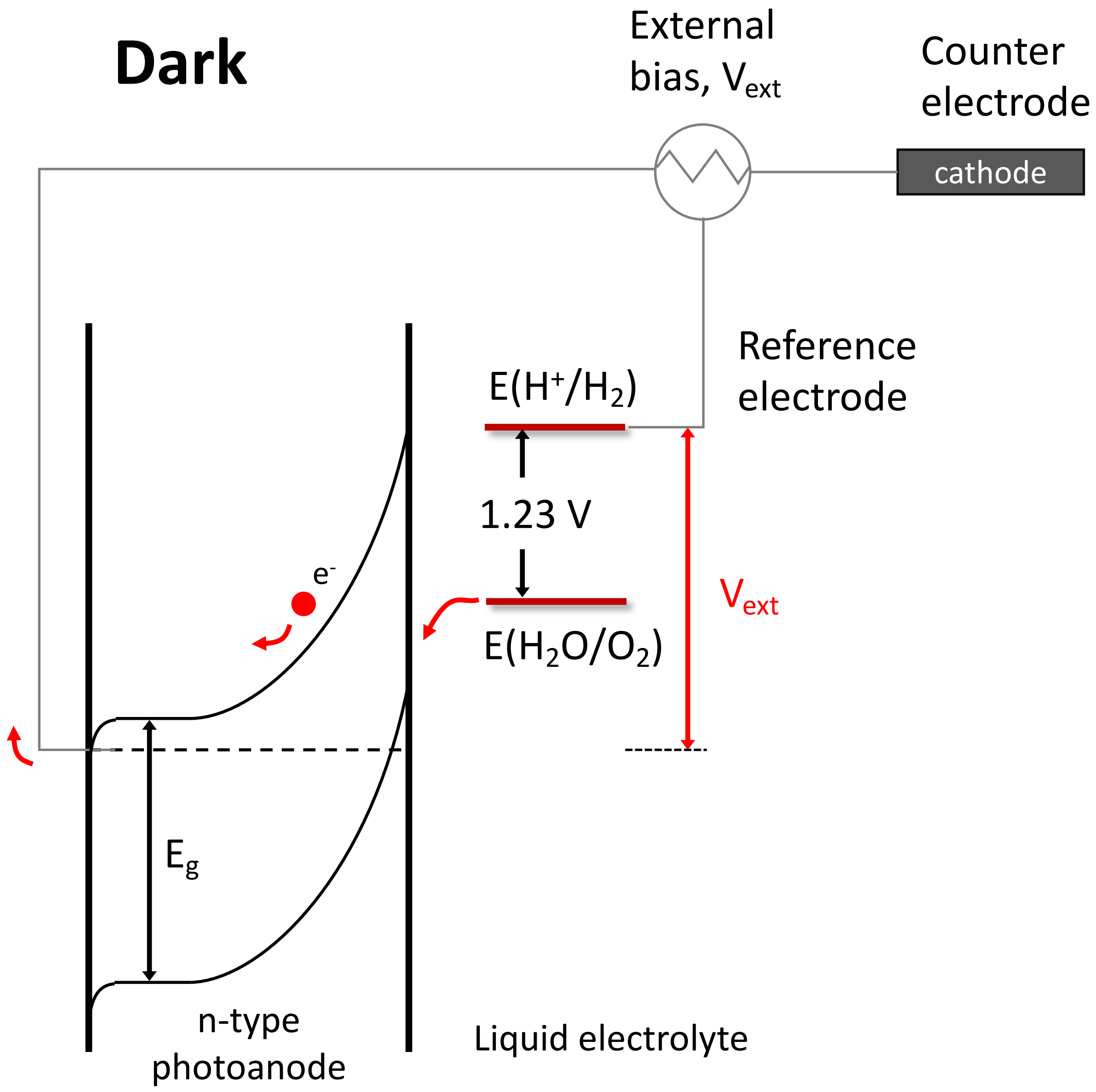
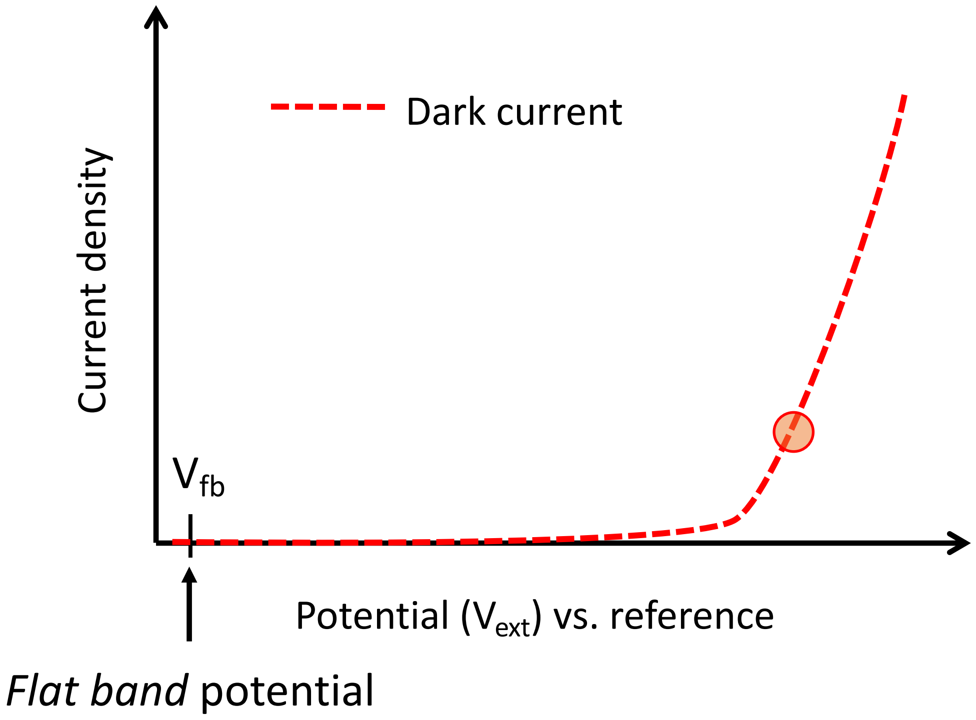
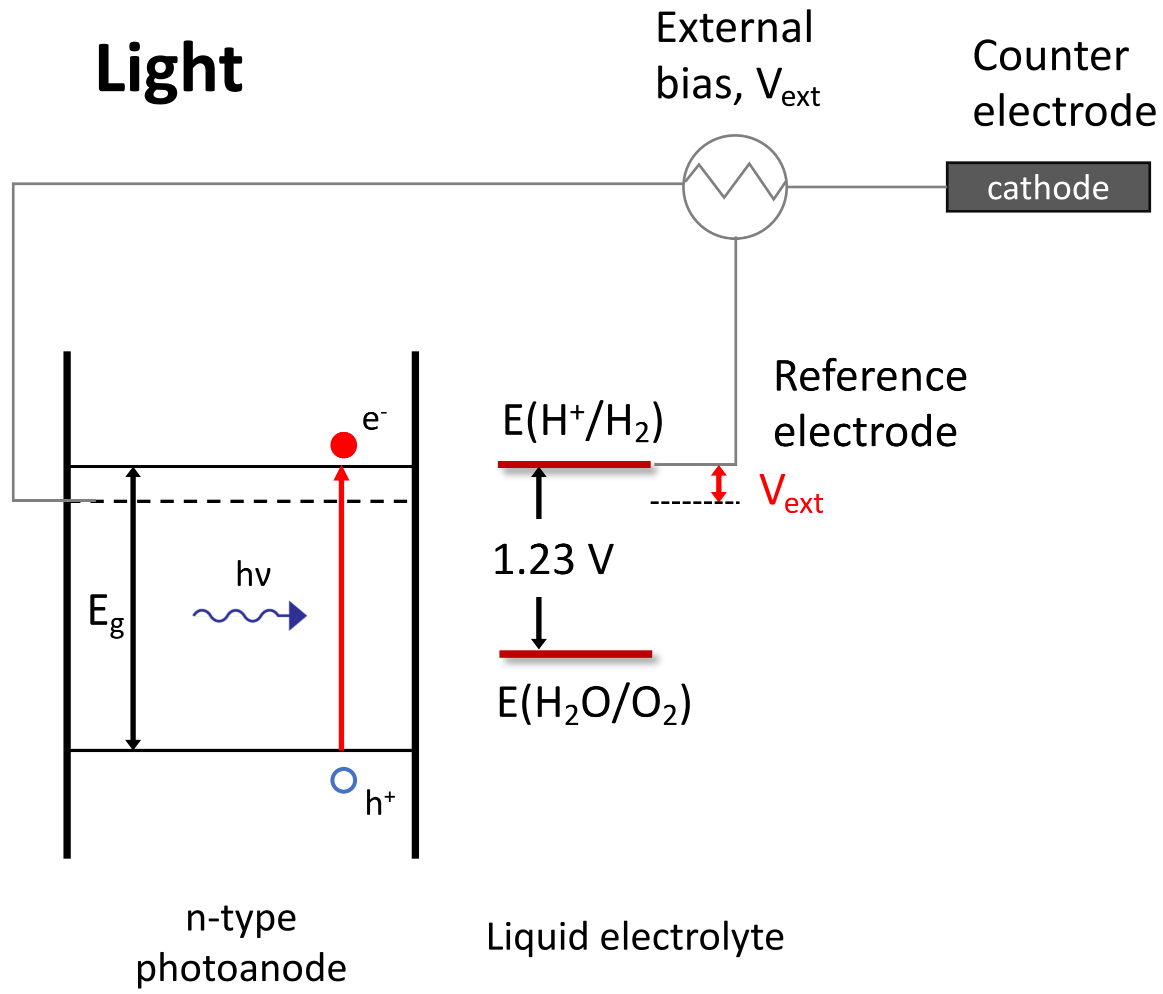
Metrics in Photoelectrode Development

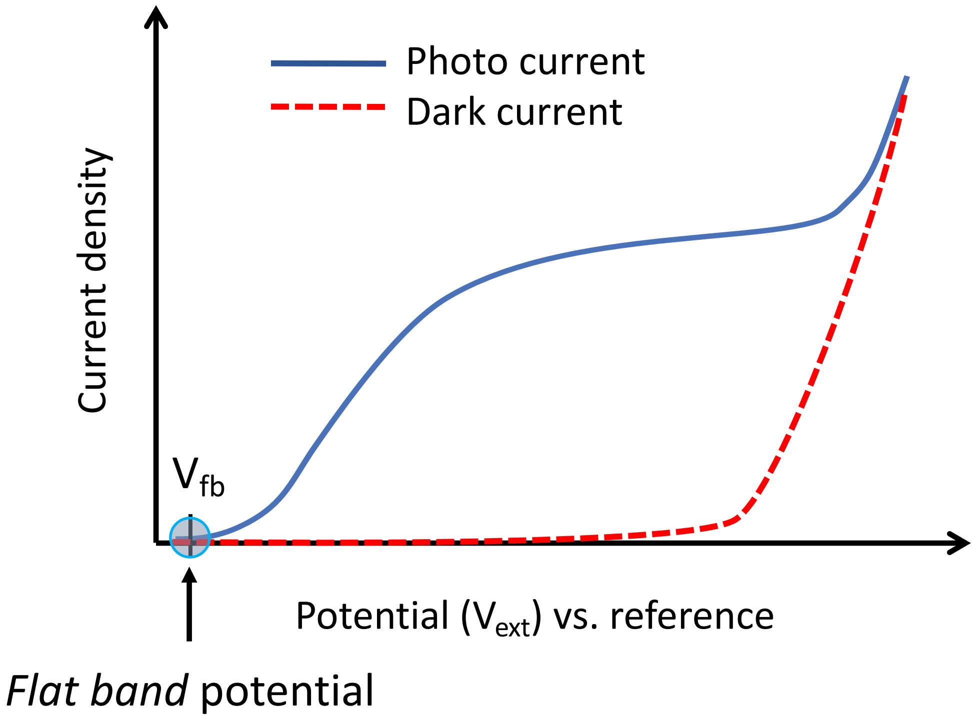




Dark current increases when energy states become available in conduction band.

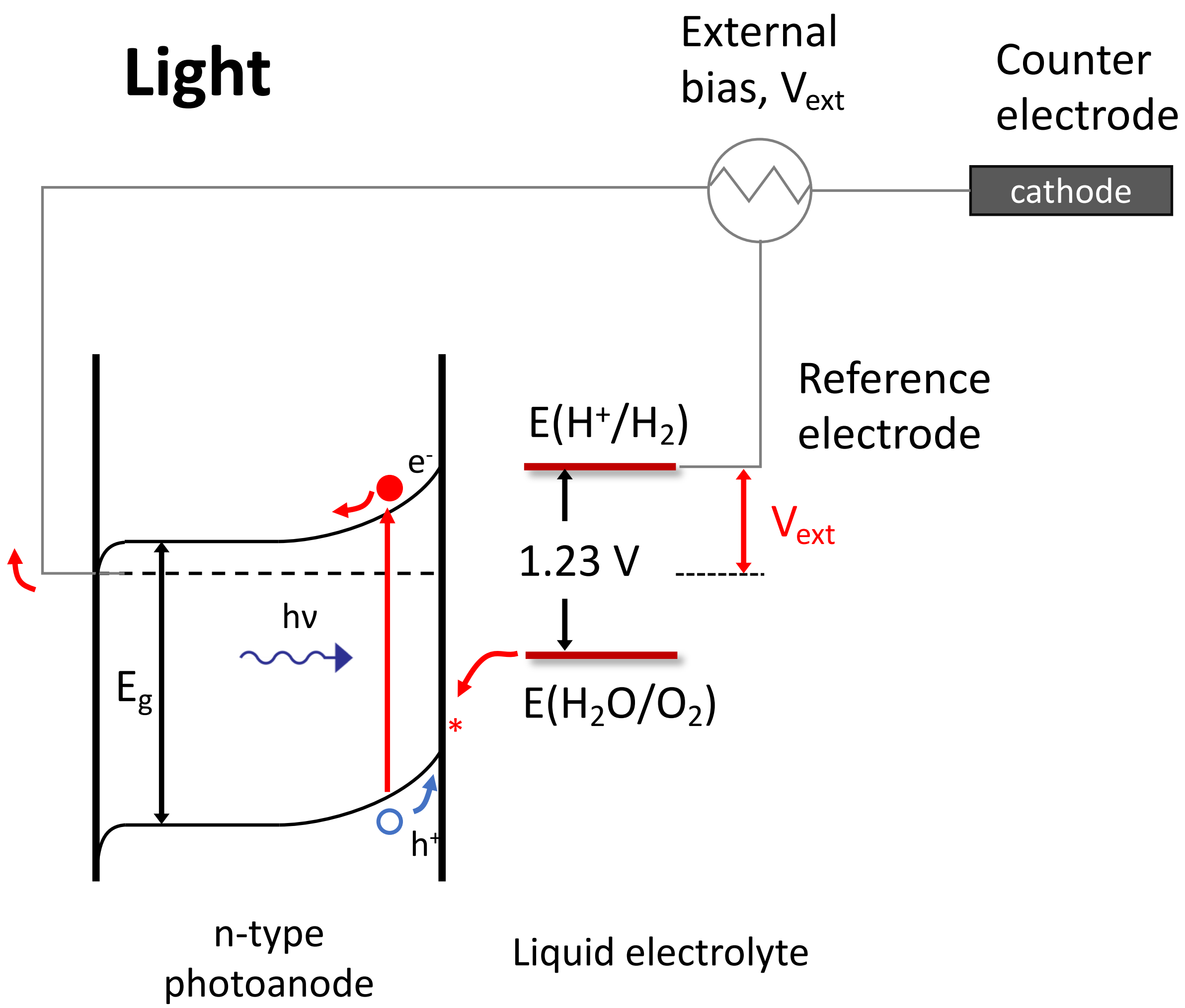
Metrics in Photoelectrode Development

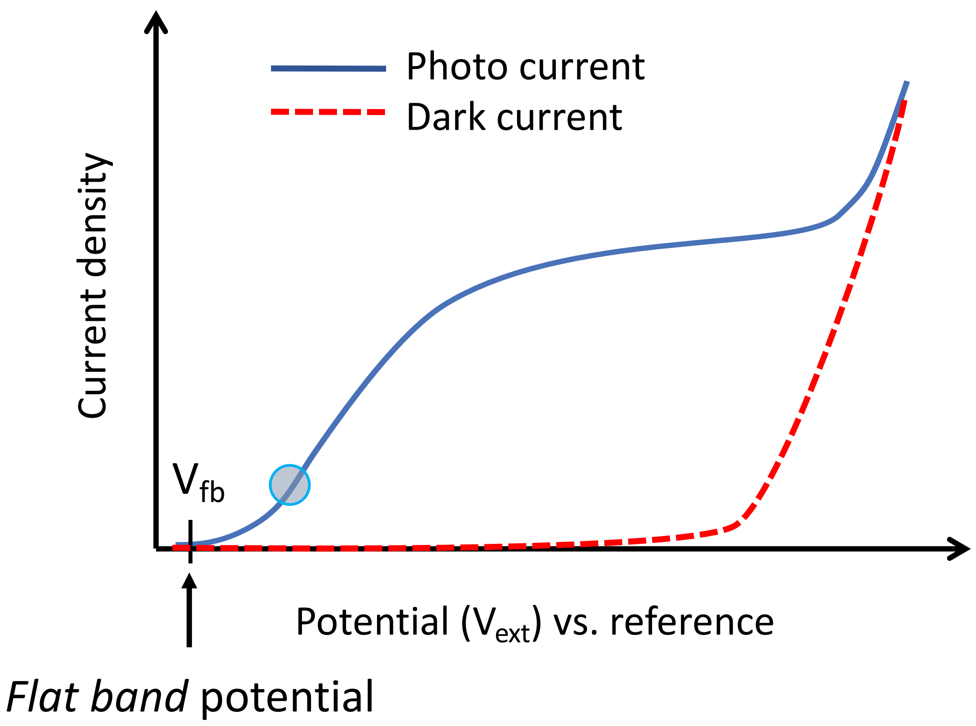




At the V_{fb}, there is no electric field to separate the photoexcited electron-hole pairs.

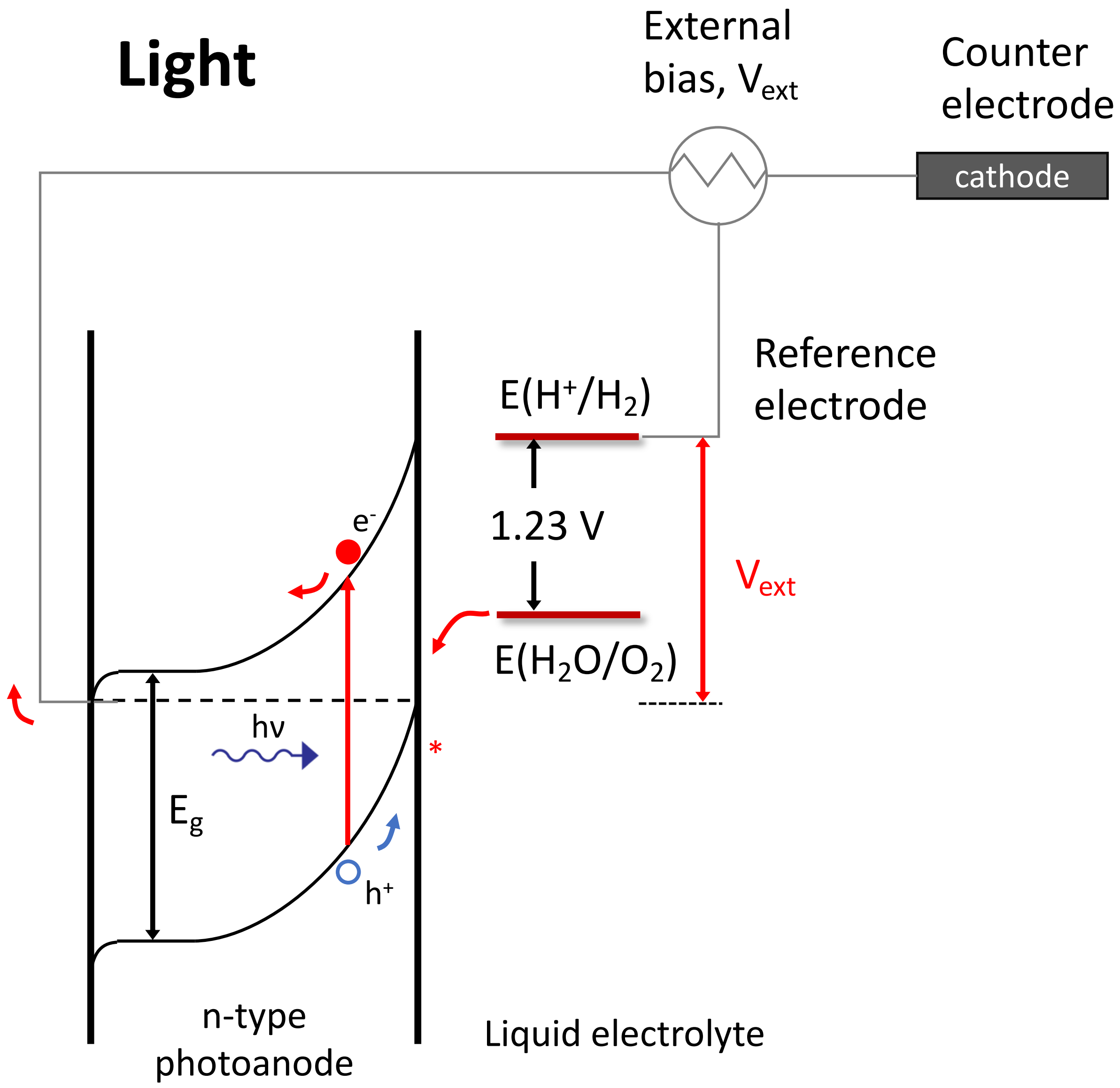
Metrics in Photoelectrode Development

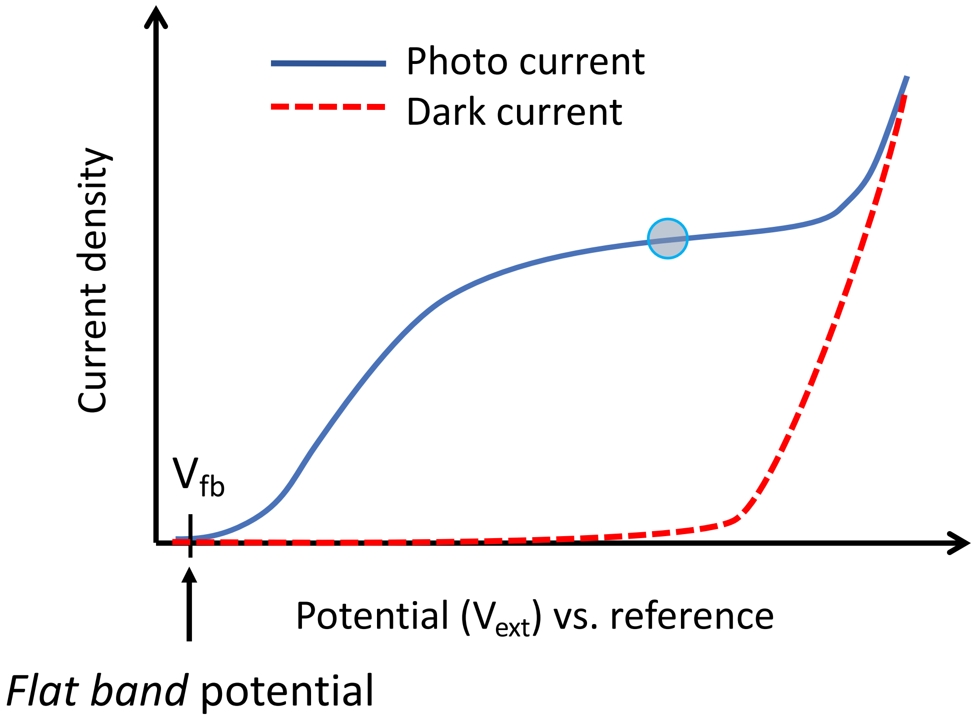




Under illumination ($h\nu > E_g$) a photocurrent is observed due to the presence of holes at the interface between the semiconductor and the electrolyte

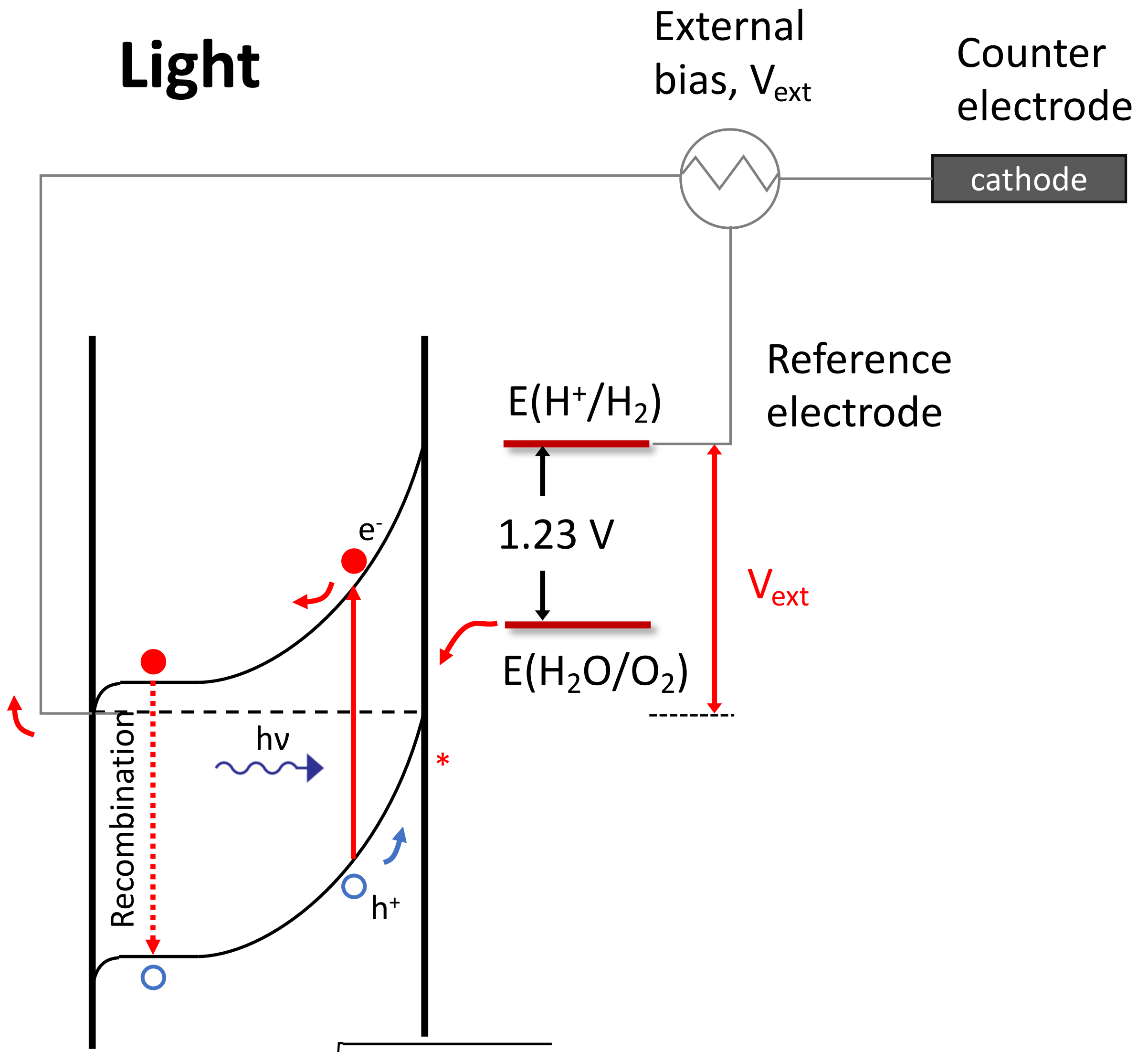
Metrics in Photoelectrode Development



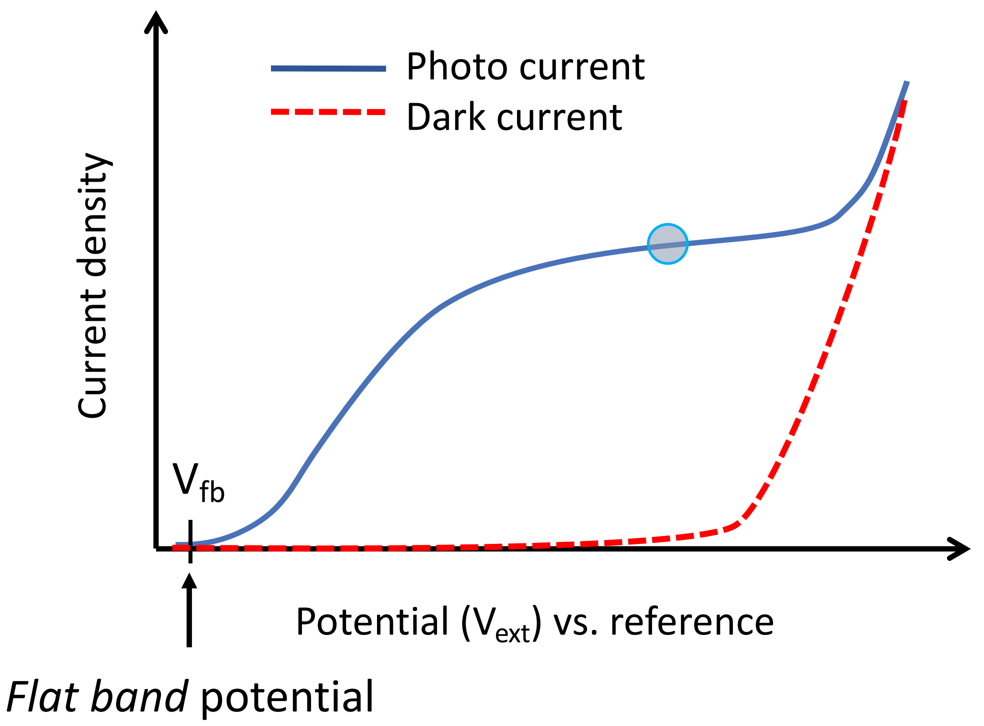


The photocurrent increases and eventually plateaus due to limitations of light absorption, surface kinetics, carrier transport, etc. Eventually, the dark current sets in.

Metrics in Photoelectrode Development



$$L_{min} = \sqrt{D_{min}\tau_{min}} = \sqrt{\frac{k_B T}{q}\mu_{min}\tau_{min}}$$



The photocurrent increases and eventually plateaus due to limitations of light absorption, surface kinetics, carrier transport, etc. Eventually, the dark current sets in.

Photoanode and Photocathode

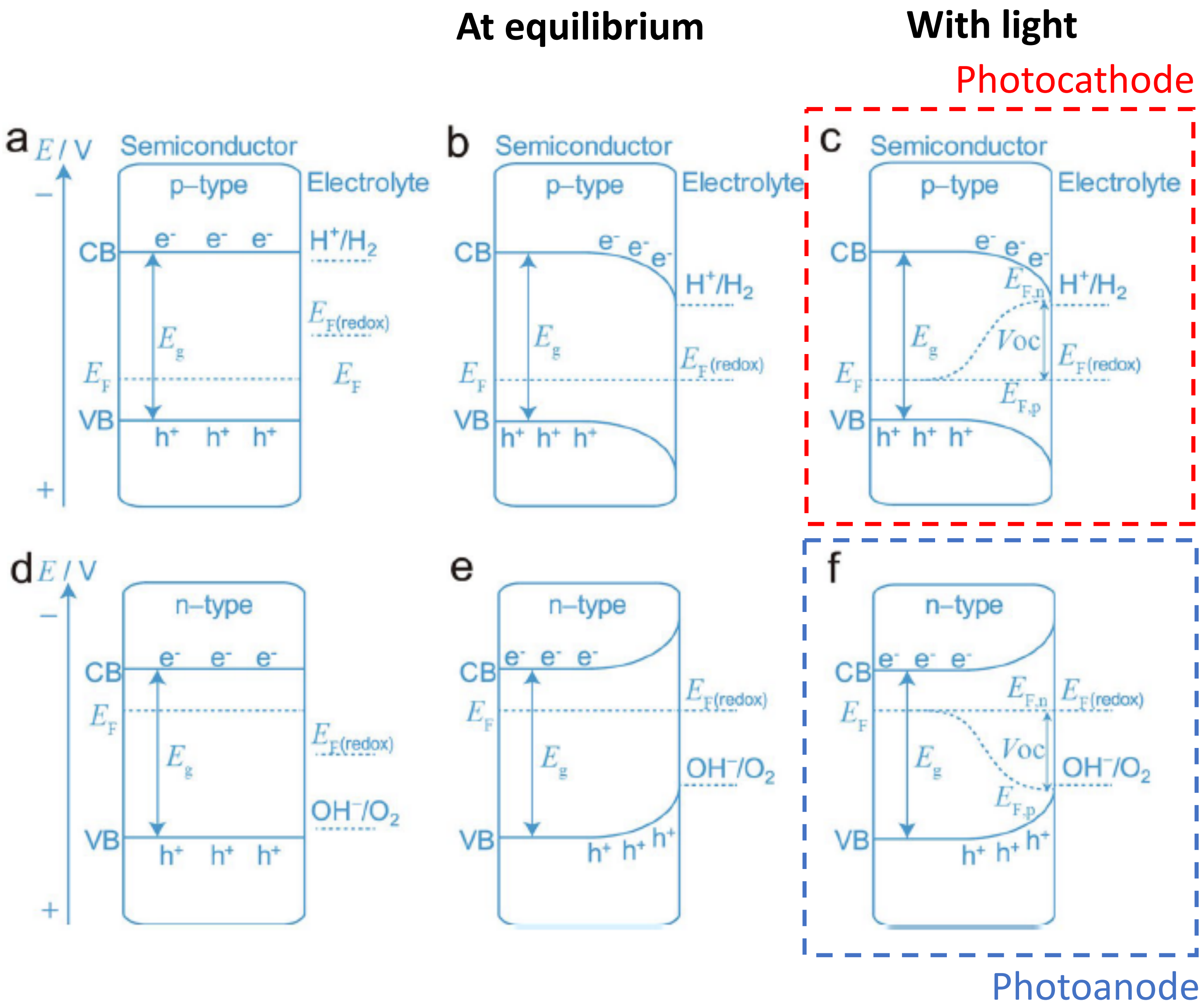
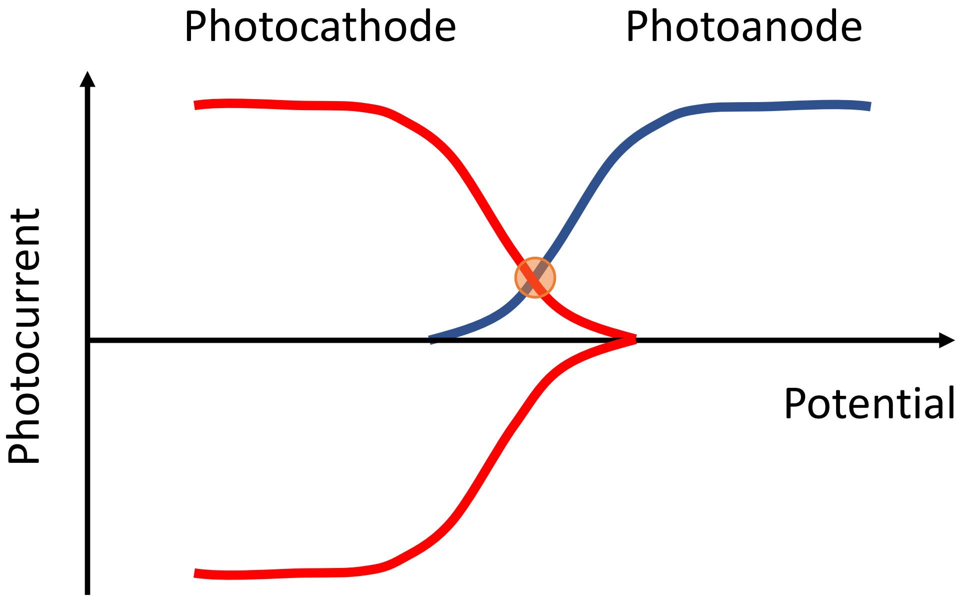
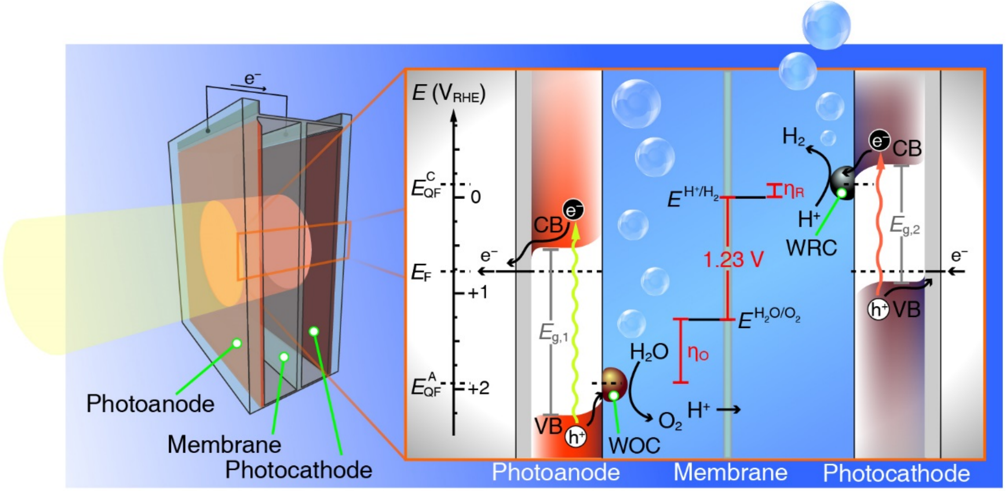


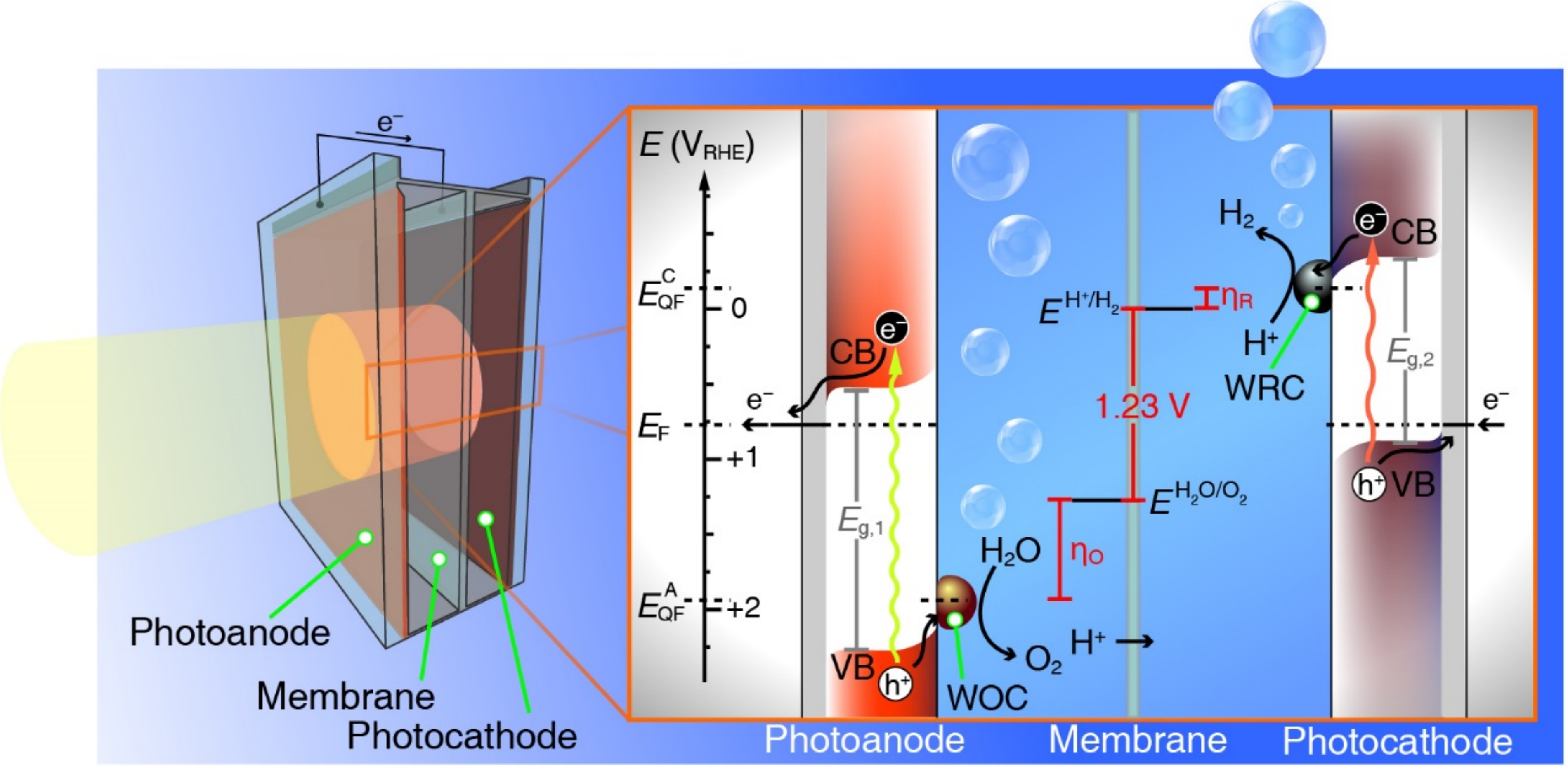
Image taken from Y- Zhao et al., Electrochem. Energy Rev., 6:14 (2023)





Tandem PEC Cell

CB of photocathode higher than $E^{H+/H2} + \eta_{HER}$



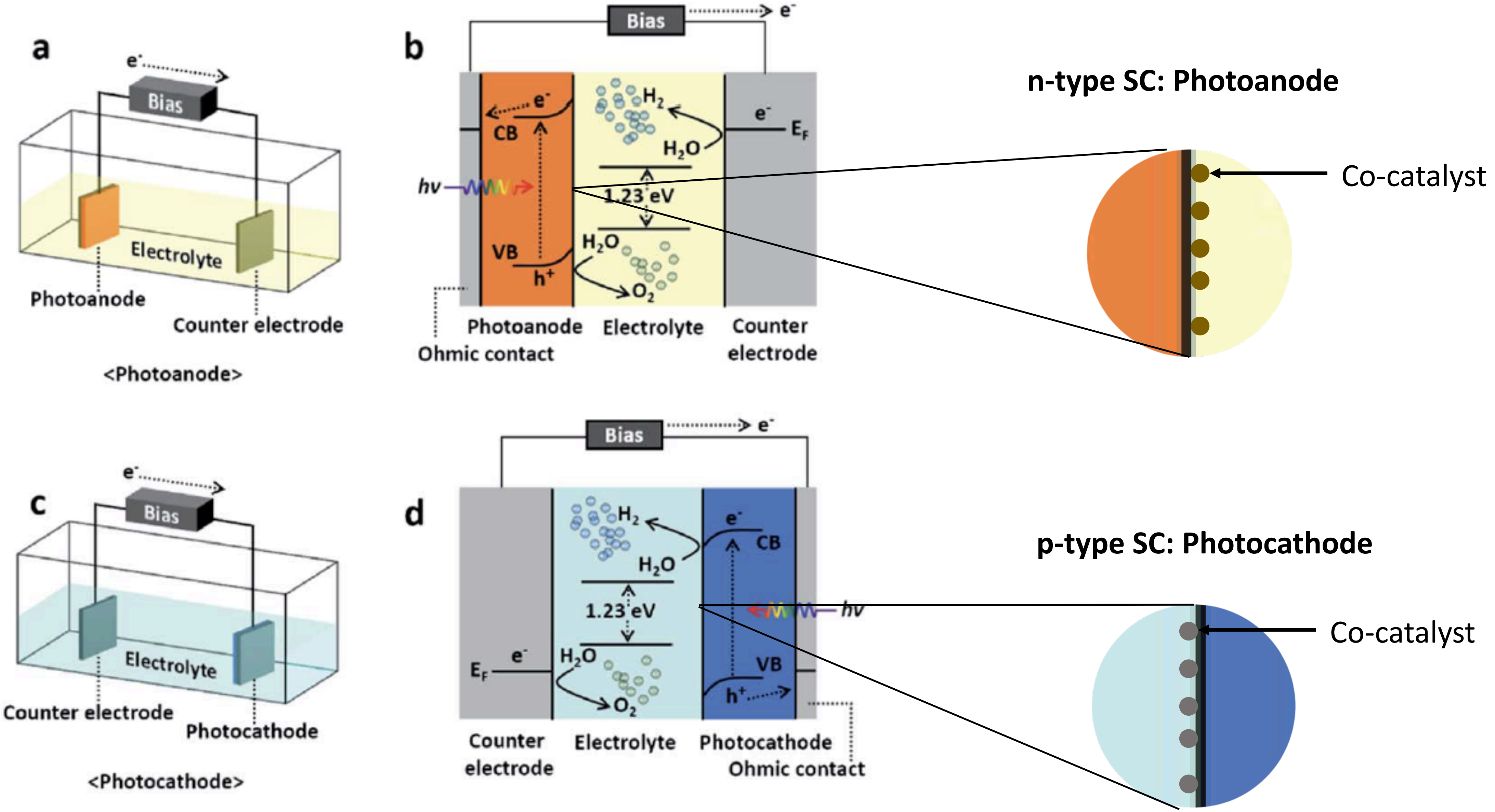
$E_{g,1} > E_{g,2}$

STH 22% with 1.8 eV $E_{g,1}$ and 1.15 eV $E_{g,2}$

VB of photoanode lower than $E^{H2O/O2} + \eta_{OER}$

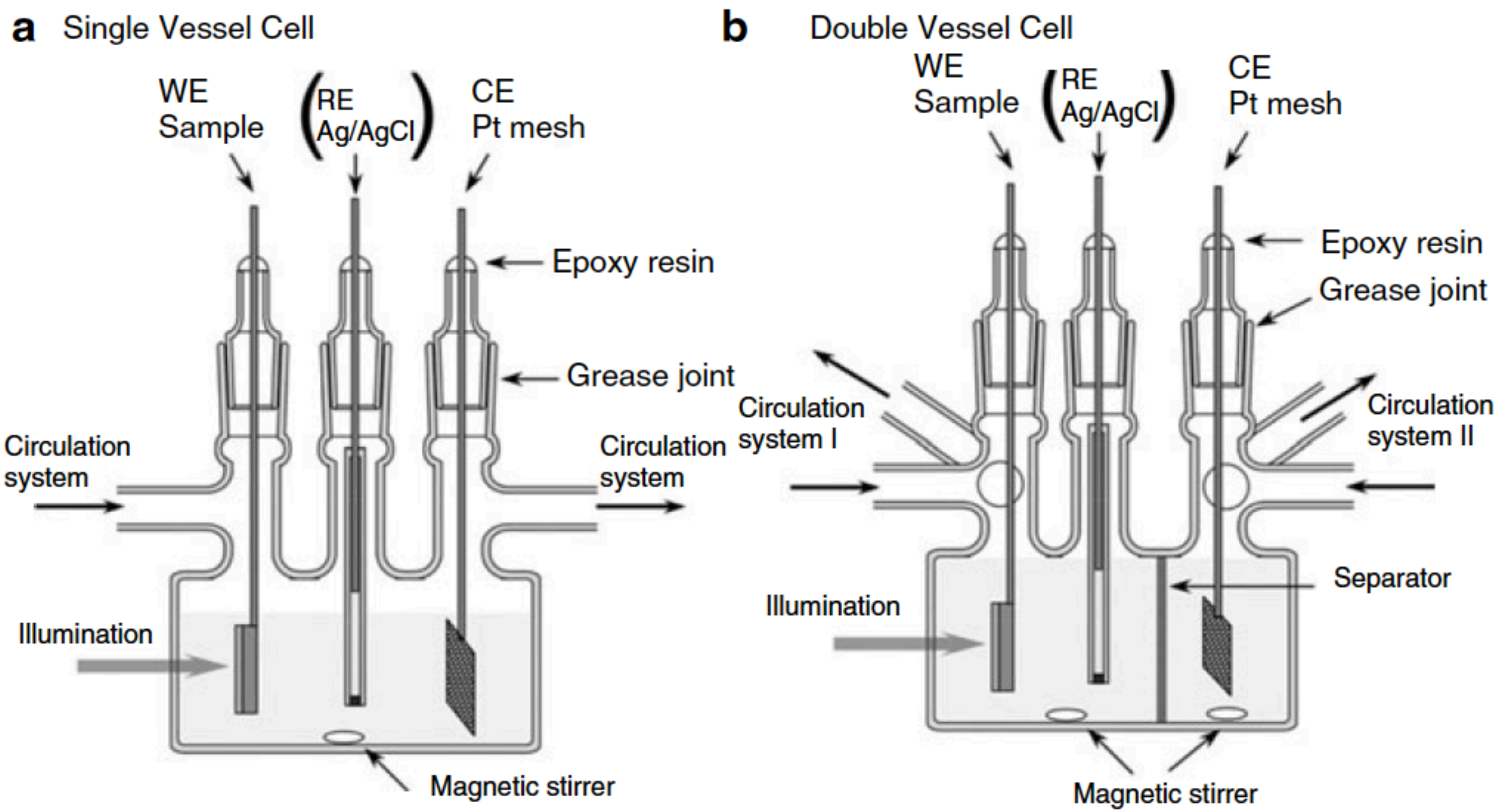
WRC: water reduction catalyst
WOC: water oxidation catalyst

Photoanode and Photocathode



Park et al., *RSC Adv.*, **9**, 30112 (2019)

Photoelectrochemical Test Setup



Z. B. Chen et al., *J. Mater. Res.,* **25**, 3–16 (2010)

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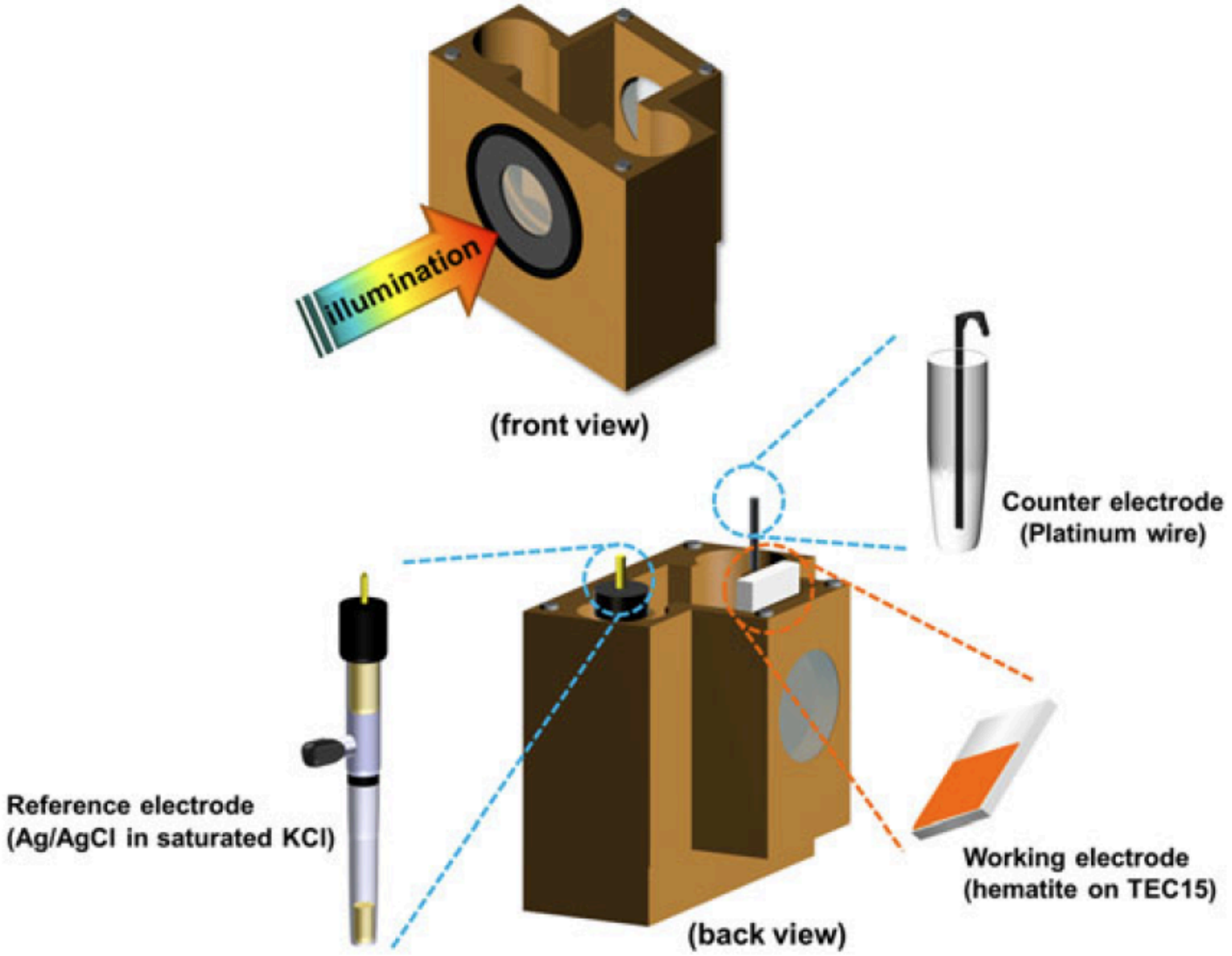
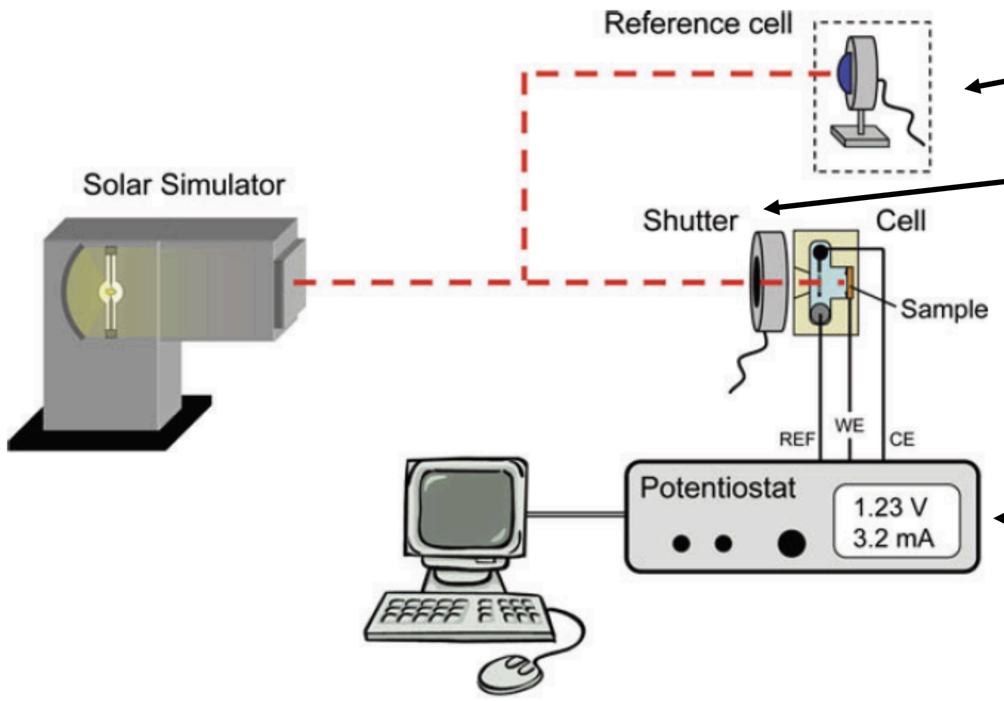
Photoelectrochemical Test Setup



EPFL Photoelectrochemical Test Setup



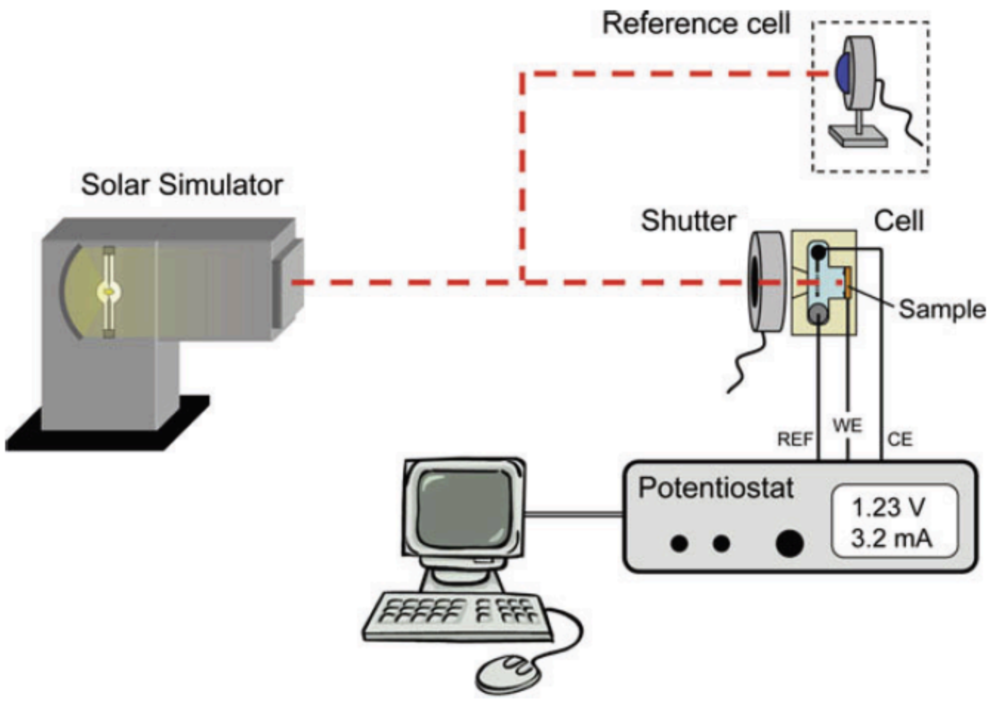
Verify the intensity of the solar simulator

Block the light, e.g. chopped light experiments

Control the sample's potential
Measure the current

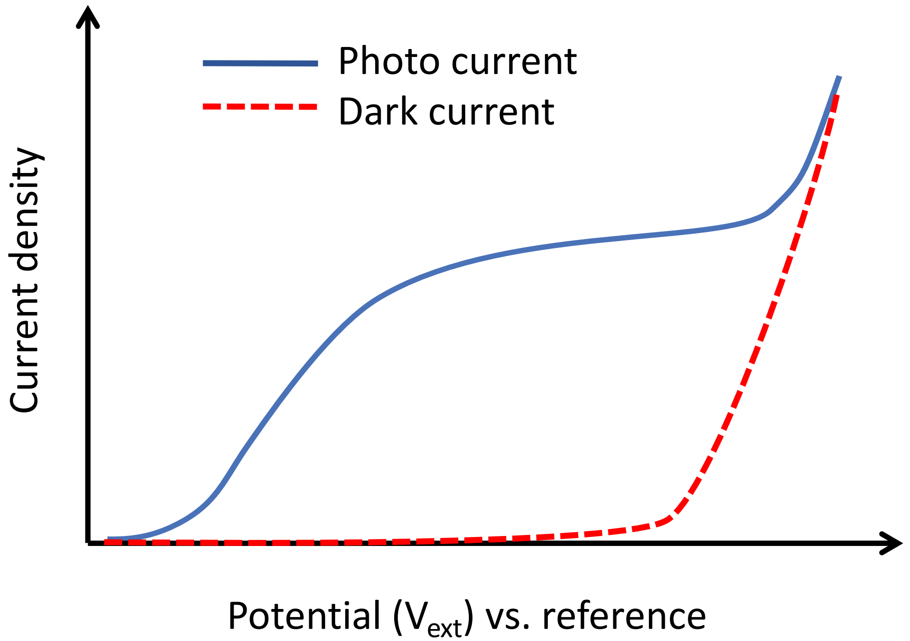
Experimental setup for measuring the performance of a photoelectrode under irradiation with simulated sunlight.

Photoelectrochemical Test Setup



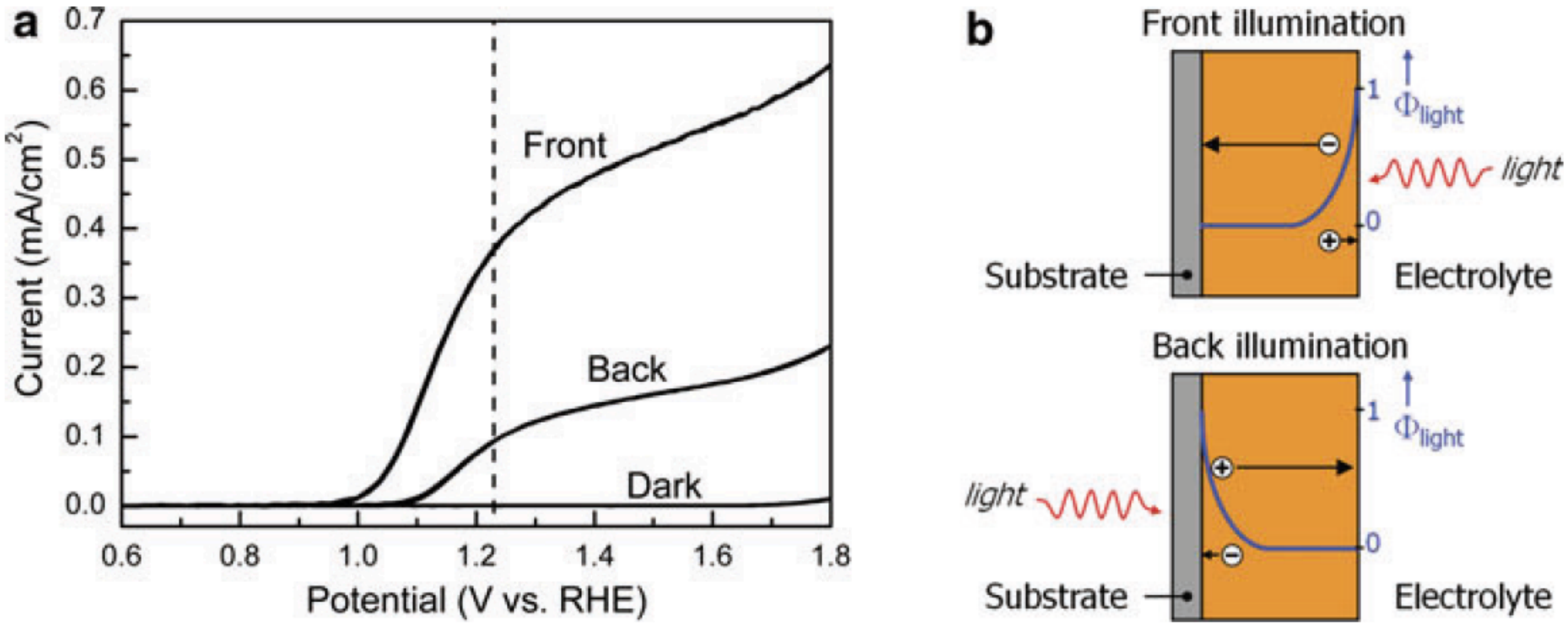
Experimental setup for measuring the performance of a photoelectrode under irradiation with simulated sunlight.

Current-Voltage Curve



Photoelectrochemical Measurements

Front- and Back-side Illumination



The curved line represents the exponentially decaying light intensity in the film.

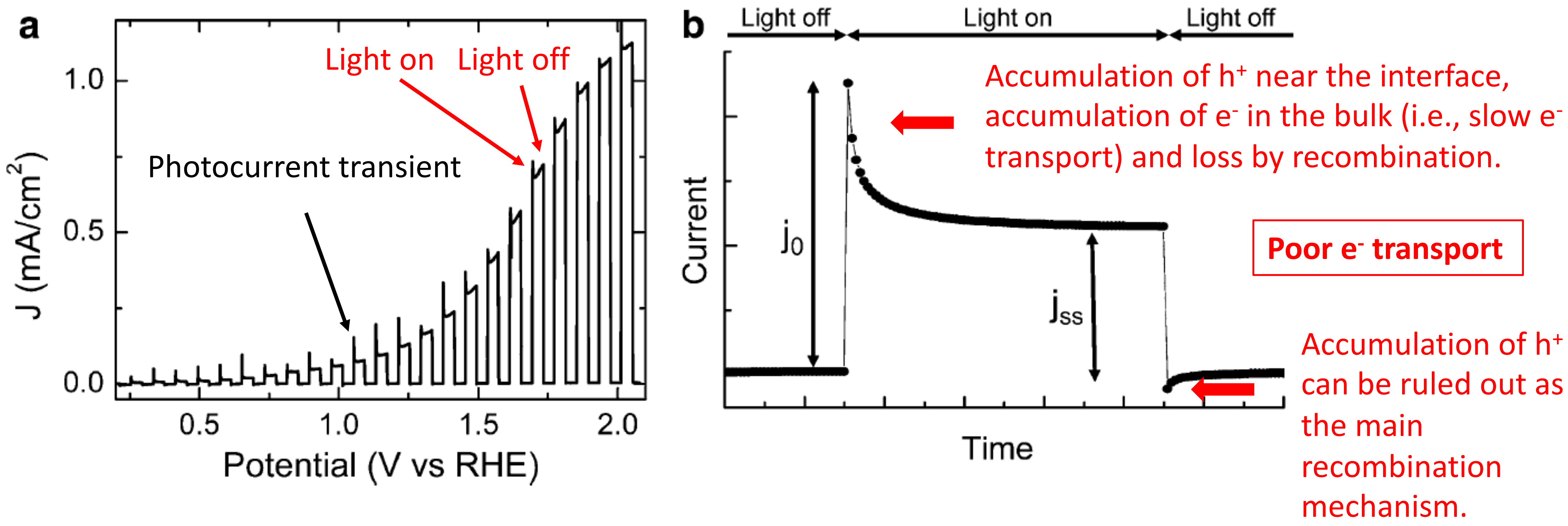
h$^+$ transport is more difficult than e- transport in Fe_2O_3!

Current–voltage curve of a spray-deposited film of 0.2% Si-doped a-Fe_2O_3 in the dark and under continuous front- or back-side illumination with 80 mW/cm^2 simulated sunlight.

Y. Liang et al., Int. J. Photoenergy, Article ID 739864 (2008).

Under front-side illumination, most light is absorbed near the semiconductor/electrolyte interface.
This means that the photogenerated electrons have to travel a larger distance before reaching the interface than the photogenerated holes.
For backside illumination, the situation is reversed.

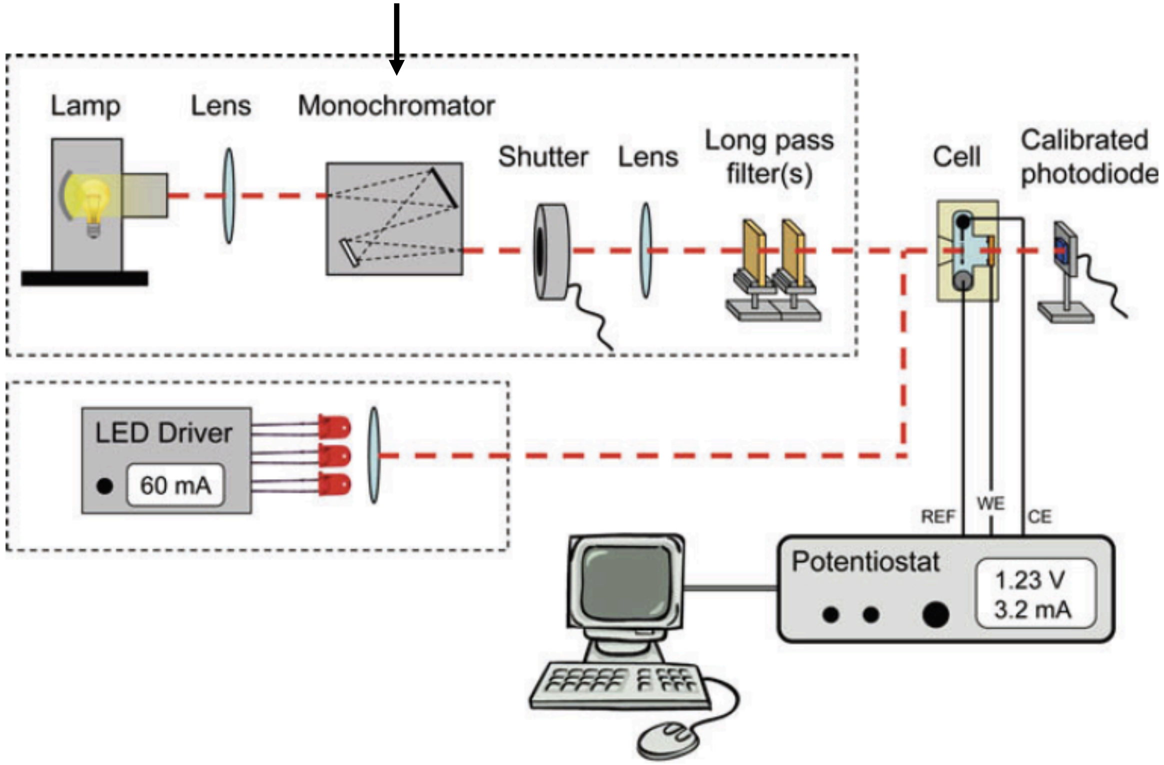
Chopped Voltammogram

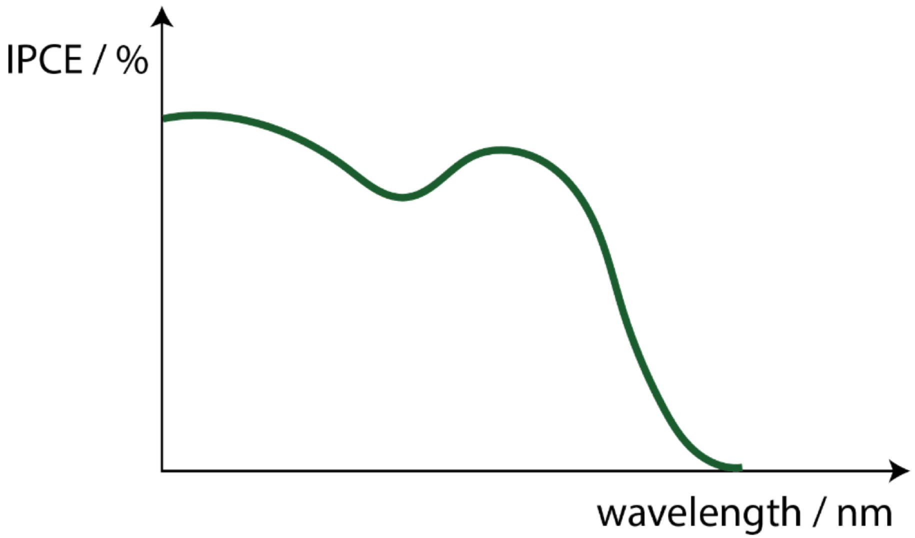


(a) Voltammogram for a spray-deposited $BiVO_4$ **photoanode** on FTO glass under chopped AM1.5 illumination.
(b) Current vs. time curve for $BiVO_4$ under high-intensity illumination with 364 nm light from a continuous-wave Ar^+ laser at a potential of 1.23 V_{RHE}. In both cases, a 0.15 M K_2SO_4 aqueous electrolyte solution was used.

Photoelectrochemical Test Setup: EQE

A monochromator is used to filter out a narrow part of the spectrum centered around the wavelength of interest.





Experimental setup for measuring the photocurrent and/or quantum efficiency as a function of wavelength.

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IPCE, APCE and ABPE

Incident Photon-to-Current (Conversion) Efficiency (IPCE) or External Quantum Efficiency (EQE) =

$$\frac{Collected\ electrons\ at\ a\ given\ wavelength}{Photons\ in\ at\ a\ given\ wavelength} = \frac{J_{SC}/q}{P_{in}/h\upsilon} = \frac{J_{SC}(A/cm^2)}{P_{in}(W/cm^2)} \times \frac{1240}{\lambda(nm)} \times 100$$

Absorbed Photon-to-Current (Conversion) Efficiency (APCE) or Internal Quantum Efficiency (IQE) =

$$\frac{electrons/sec}{absorbed\ photons/sec} = \frac{EQE}{1-R-T} = \frac{EQE}{LHE}$$

Applied Bias Photon-to-Current (Conversion) Efficiency (ABPE or ABPC) =

$$\frac{(Total\ power\ output\ - Electrical\ input\ power)}{Light\ power\ input} = \frac{J_{SC} \times (1.23 - |V_a|) \times \eta_F}{P_{in}}$$

Faraday Efficiency

Faraday efficiency (also called faradaic efficiency, faradaic yield, coulombic efficiency or current efficiency) **describes the efficiency with which charge (electrons) is transferred in a system facilitating a desired electrochemical reaction**. In other words, the faraday efficiency is the ratio of experimentally measured moles of gas divided by the theoretical number of moles of product gas.

$$\eta_F = \frac{n_{prod}}{Q/nF}$$

n_{prod} is the gas measured experimentally in mole.
Q is the charge in coulombs corresponding to the photocurrent at time (s) (C = A x s)
F is faraday's constant (96485.33 C/mol)
n is the number of charges needed to drive the reaction

For H_2 production: $\eta_F = \frac{n_{H_2}}{Q/2F}$

For O_2 production: $\eta_F = \frac{n_{O_2}}{Q/4F}$

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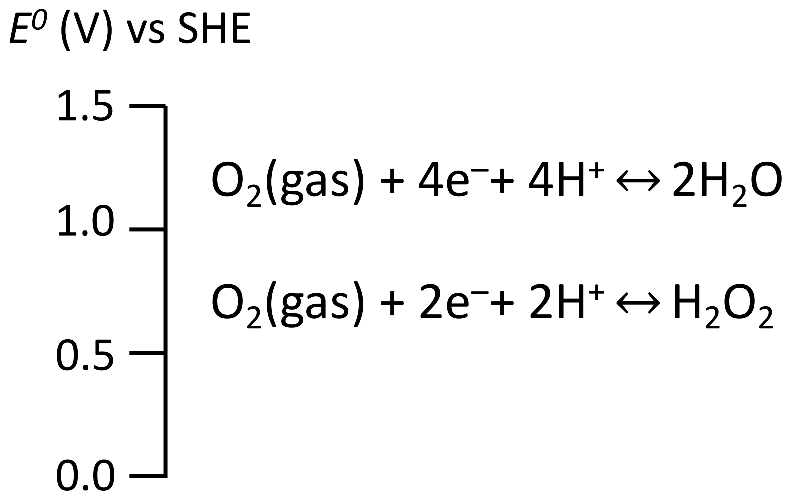
Faradaic Losses

Faradaic losses are experienced when electrons or ions participate in unwanted side reactions.
These losses appear as chemical byproducts and/or heat.

Example 1) In the oxidation of water to oxygen at the positive electrode in electrolysis, some electrons are diverted to the production of hydrogen peroxide. The fraction of electrons so diverted represent a faradaic loss.

O_2(gas) + $2e^-$+ $2H^+ \leftrightarrow H_2O_2$ (liquid)

$$E^0_{H_2O_2/O_2} = 0.682\ V\ vs.SHE$$



EPFL Solar-To-Hydrogen Efficiency

- Solar-To-Hydrogen (STH) efficiency is defined as ***chemical energy of the hydrogen produced*** divided by ***solar energy input from sunlight incident on the process***.

- The ***chemical energy of the hydrogen produced*** = The rate of hydrogen production (mmol H_2/s) multiplied by the change in Gibbs free energy per mole of H_2 ($\Delta G^0 =$ 237.2 kJ/mol at 25 °C).

$$\boldsymbol{STH} = \left[\frac{(mmol\ H_2/s) \times (237{,}200\ J/mol)}{P_{total}\left(\frac{mW}{cm^2}\right) \times Area\ (cm^2)}\right]_{AM1.5G}$$

This equation calculates the power output (numerator) based on the direct measurement of the true H_2 production rate by an analytical method such as gas chromatography or mass spectrometry.

$$\boldsymbol{STH} = \left[\frac{(J_{sc}\ (mA/cm^2) \times (1.23\ V) \times \eta_F}{P_{total}\left(\frac{mW}{cm^2}\right)}\right]_{AM1.5G}$$

Alternatively, this equation uses the relation that power is the product of the minimum energy to split water, current, and the Faradaic efficiency for hydrogen evolution

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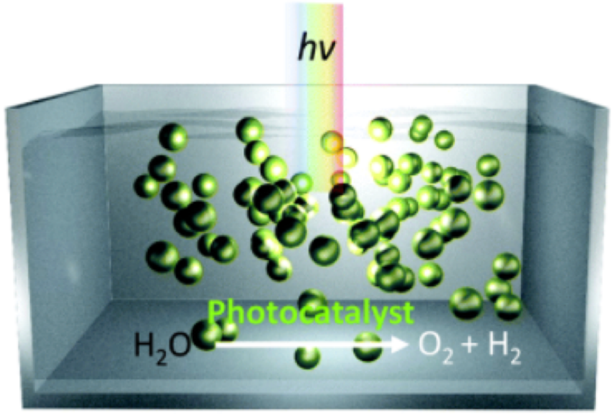
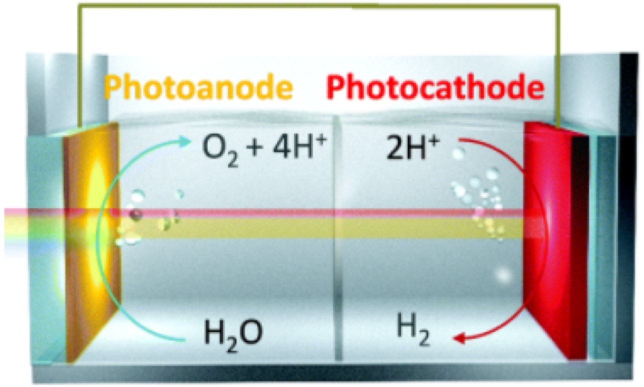
Solar-To-Hydrogen Efficiency

PC



PEC



$$\boldsymbol{STH} = \left[\frac{(mmol\ H_2/s) \times (237{,}200\ J/mol)}{P_{total}\left(\frac{mW}{cm^2}\right) \times Area\ (cm^2)}\right]_{AM1.5G}$$

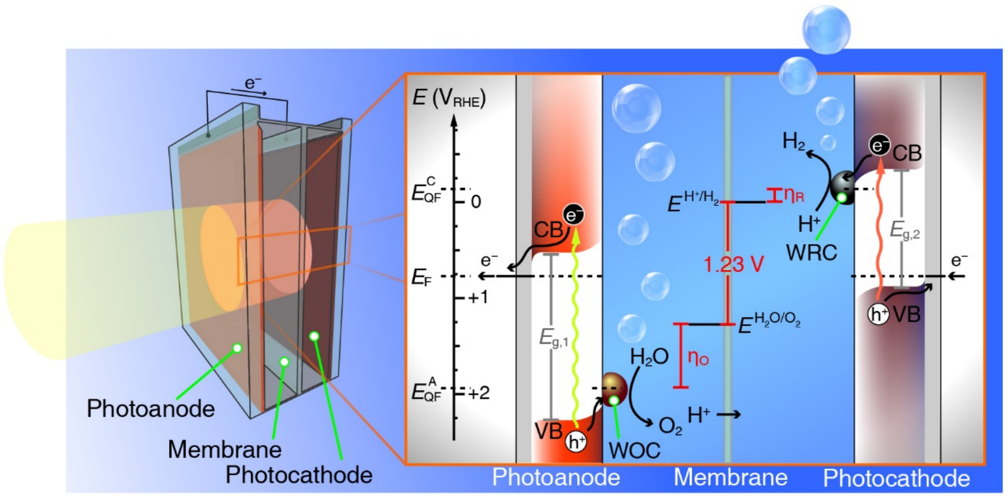
$$\boldsymbol{STH} = \left[\frac{(J_{sc}\ (mA/cm^2) \times (1.23\ V) \times \eta_F}{P_{total}\left(\frac{mW}{cm^2}\right)}\right]_{AM1.5G}$$

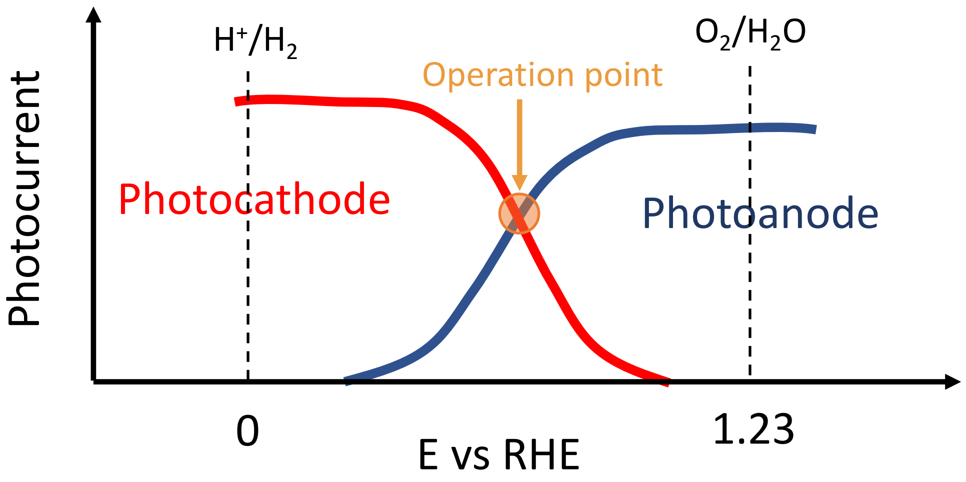
Solar-To-Hydrogen Efficiency

- Benchmark efficiency (suitable for mainstream reporting of stand-alone water splitting capability)
  – solar-to-hydrogen conversion efficiency (STH)

- Diagnostic efficiencies (to characterize and understand materials system/interface performance)
  – external quantum efficiency (EQE) = incident photon-to-current efficiency (IPCE)
  – internal quantum efficiency (IQE) = absorbed photon-to-current efficiency (APCE)
  – applied bias photon-to-current efficiency (ABPE)

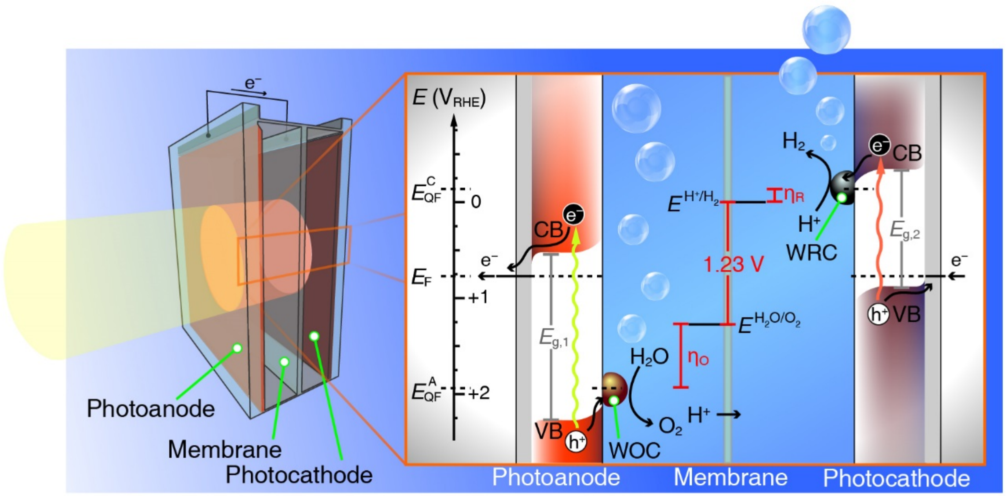
Assessment of a Dual Tandem PEC Cell

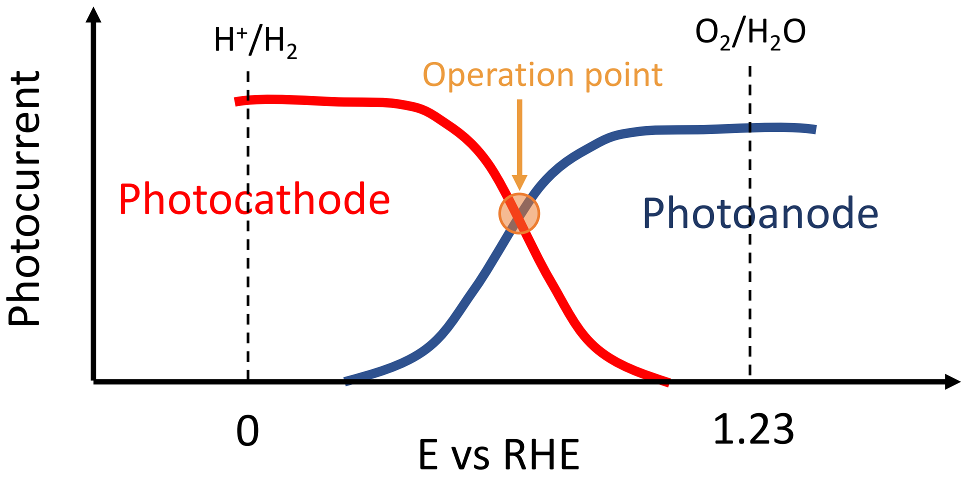




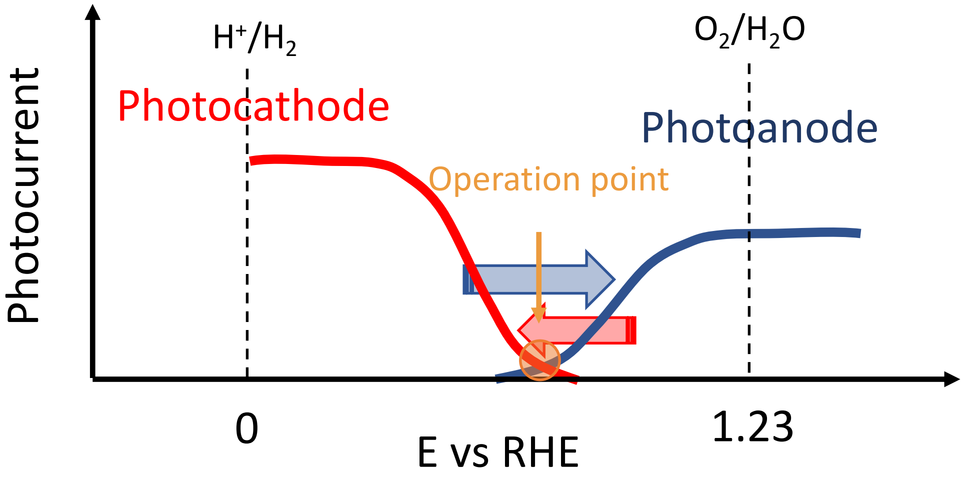
Examine separately photoelectrodes.
Predict 'best' performance (*overlapping of JV curves*)

Assessment of a Dual Tandem PEC Cell





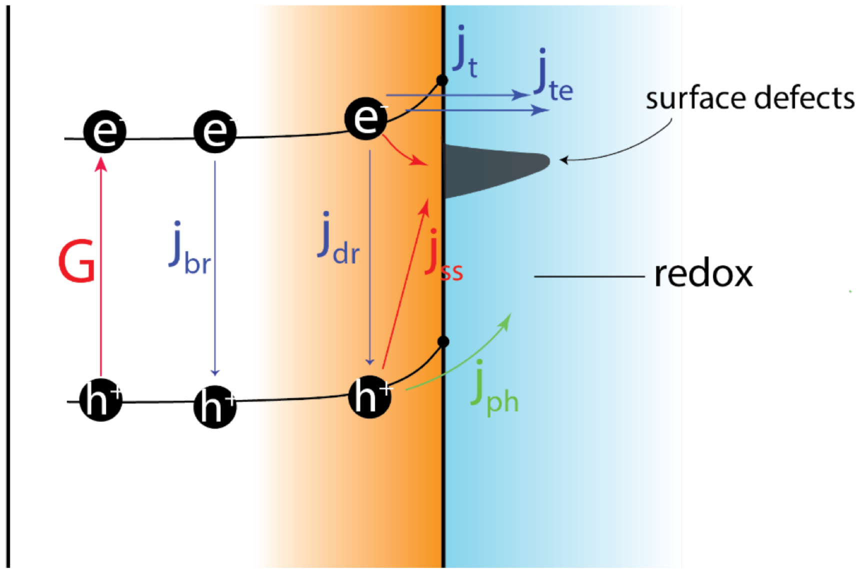
Real



Today's low-cost PEC cells suffer from poor STH

- Poor performance of photoelectrodes
- Non-optimized combination of photoelectrodes (band gaps)

Challenges to Address



$$J_{ph} = \boldsymbol{G} - J_{br} - J_{dr} - J_{ss} - J_t - J_{te}$$

- Charge recombination in the bulk (br), in the depletion layer (dr) and via surface states (ss).
- Electron losses by reaction with redox through tunneling (t) across the potential barrier or at the surface (te)

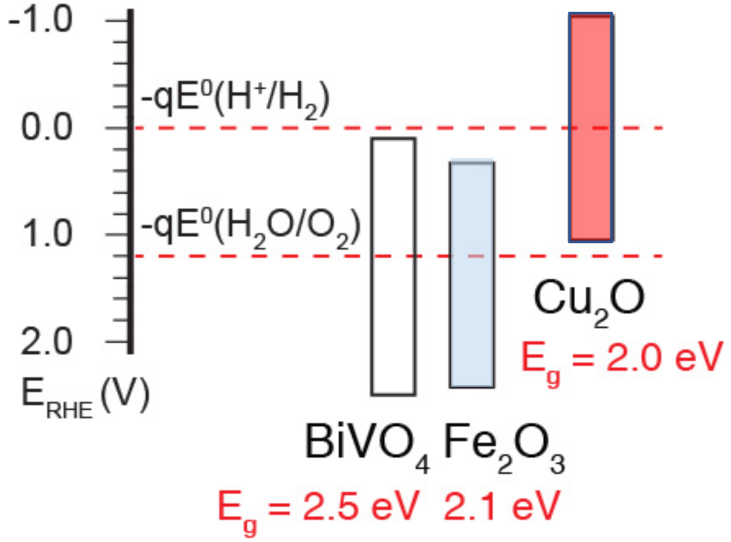
Bulk properties

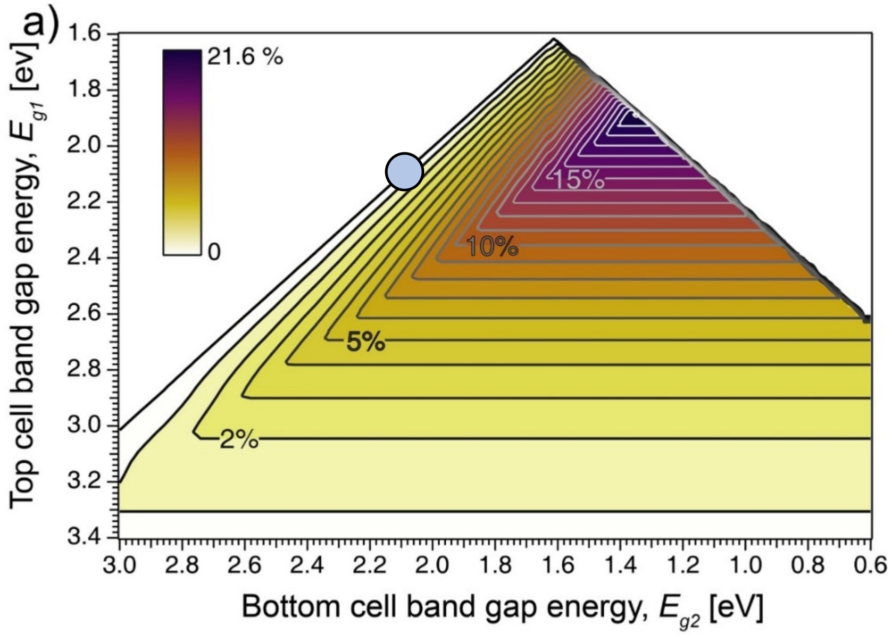
- Bulk defects (recombination)
- Carrier transport
- Doping density (conductivity, depletion depth)
- Morphology (charge collection)

Surface properties (Semiconductor-liquid junction)

- Surface defects (recombination)
- Catalytic properties
- Stability

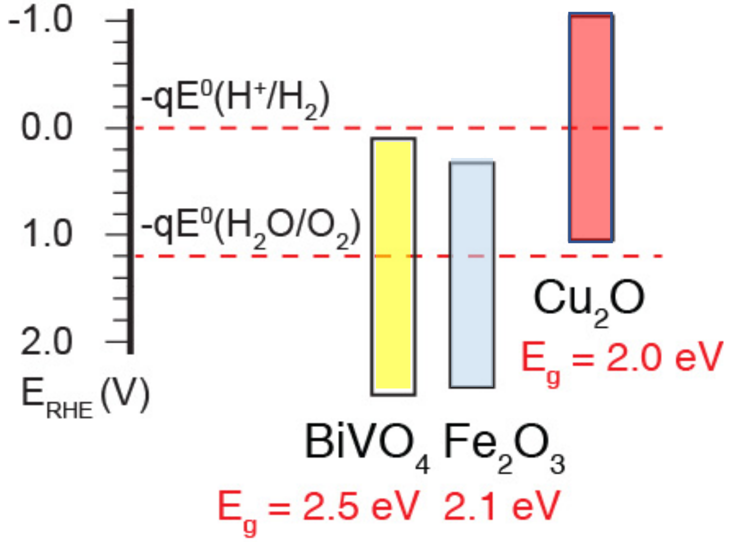
Assessment of a Dual Tandem PEC Cell

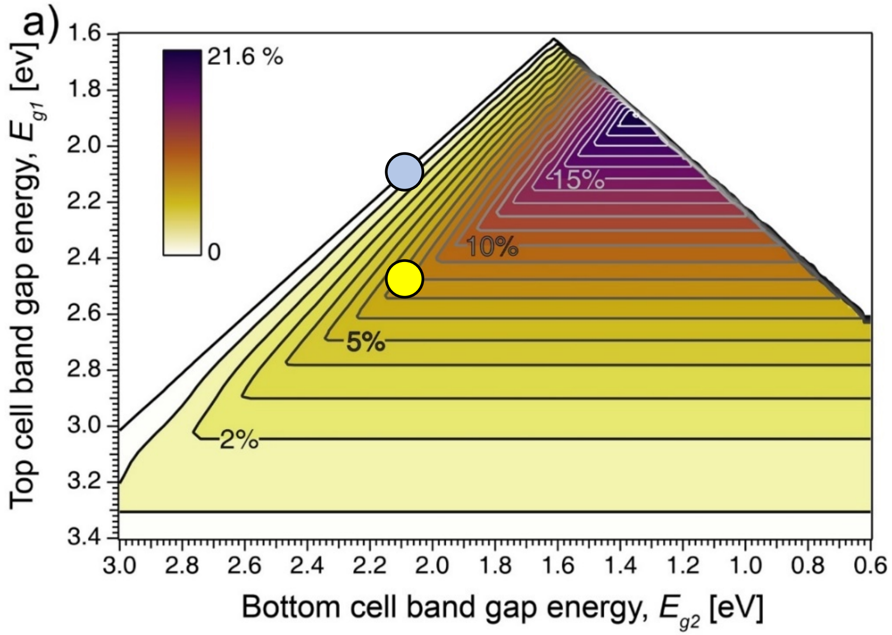


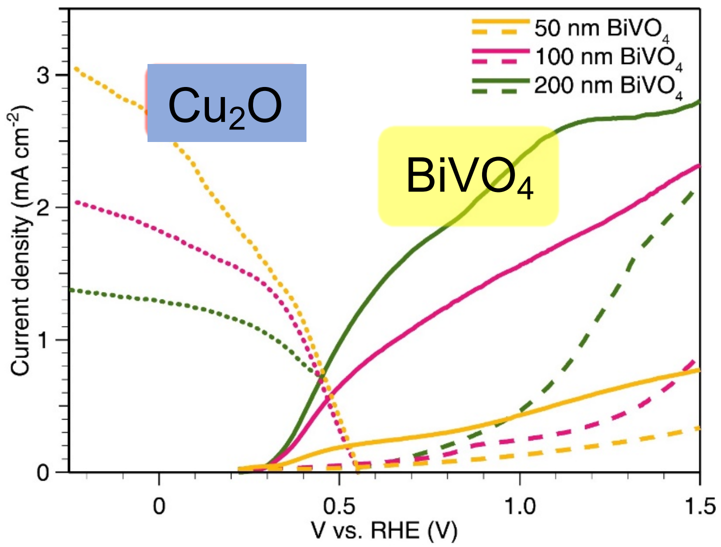


Low performance (non-complementary light absorption).
Hematite filters useful light for Cu_2O

Assessment of a Dual Tandem PEC Cell







Bornoz *et al. J.Phys. Chem. C.* **118**, 16959-16966 (2014).

Examples of Photoelectrodes

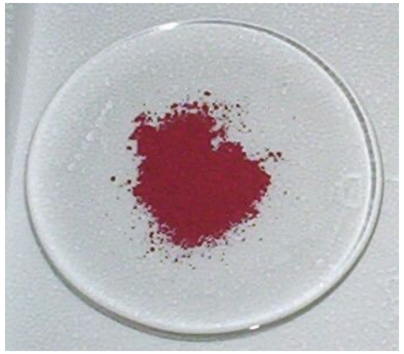
Photoanode (n-type SC)

WO_3

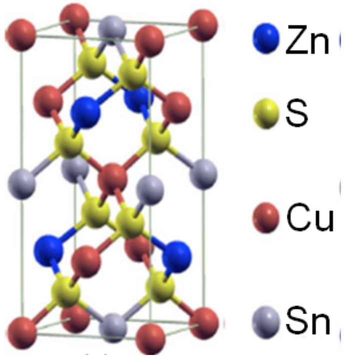
$BiVO_4$

α-Fe_2O_3

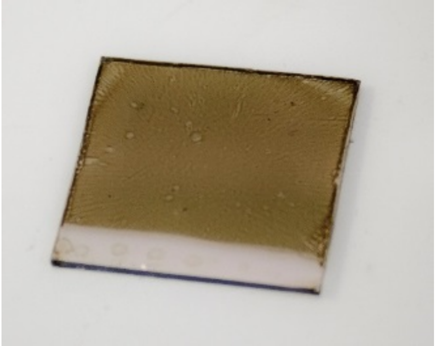
Photocathode (p-type SC)



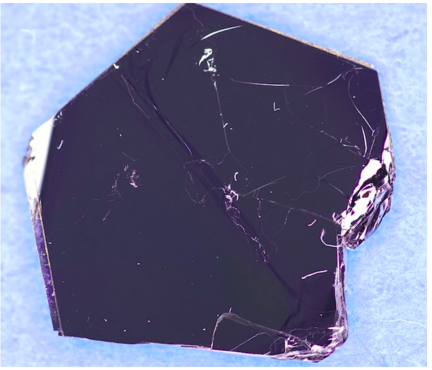
Copper(I) oxide



Cu_2ZnSnS_4



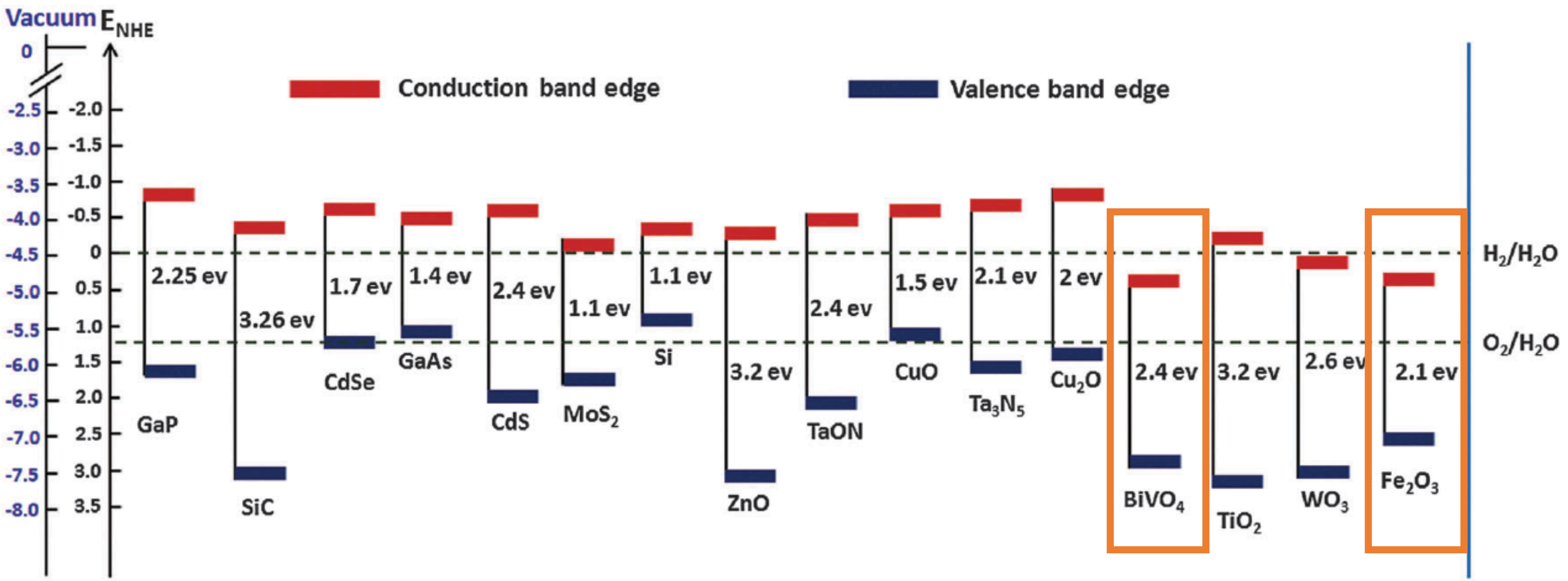
$CuFeO_2$



WSe_2

Examples of Photoelectrodes

Band edge positions of semiconductors in contact with the aqueous electrolyte at pH = 0 relative to NHE and the vacuum level.



α-Fe_2O_3 (hematite) as a Photoanode

Advantages

- Cheap and abundant (Fe in the earth crust, 6.3% by weight)
- Stable
- Environmentally benign
- Absorbs over 16 % (AM 1.5G, E_g = 2.1 eV)
- Theoretical max STH = 15%, J_{max} = 12.5 mA/cm^2

Challenges

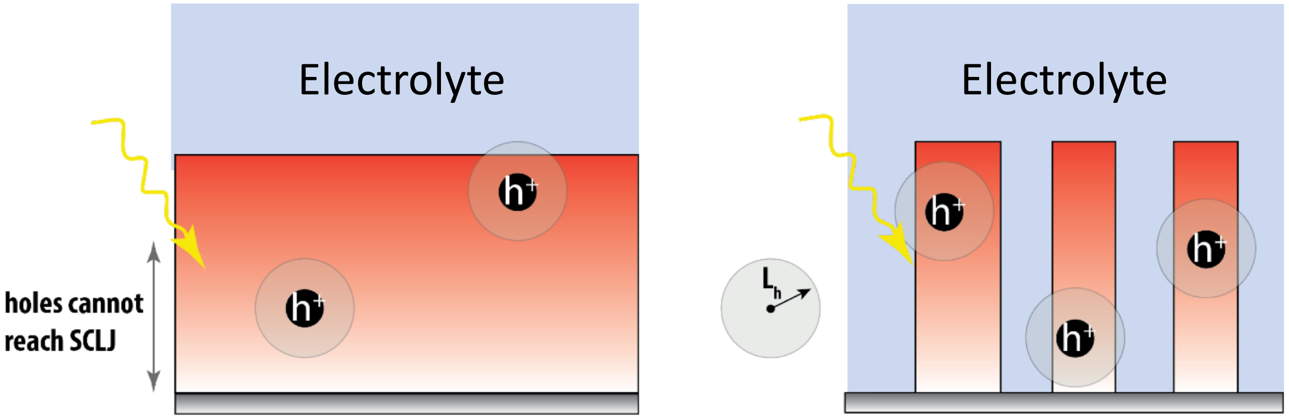
Bulk problems

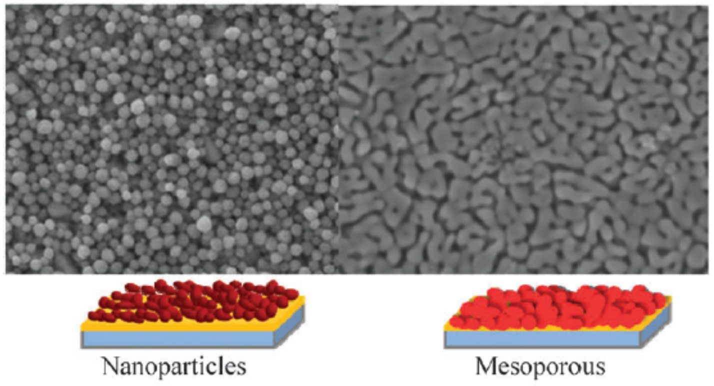
- Short hole diffusion length (**L_D = 5 nm**) (light penetration depth of 118 nm at 550 nm wavelength)
- Poor conductivity ($10^{-6}\ \Omega^{-1}cm^{-1}$ for single crystal and $10^{-14}\ \Omega^{-1}cm^{-1}$ for polycrystal)

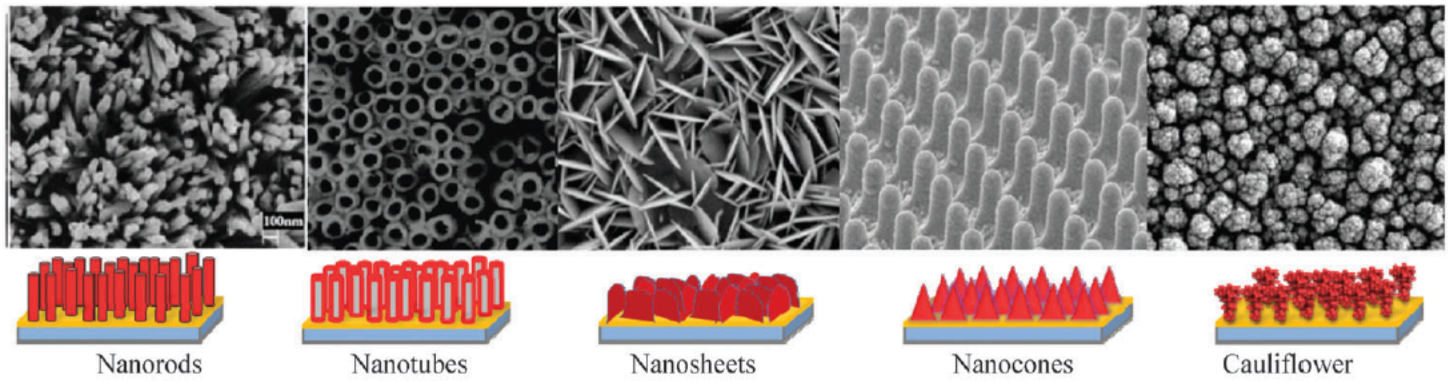
Surface problems

- High overpotential for water oxidation kinetics (surface trap states)

Bulk Problems in α-Fe_2O_3 (hematite)

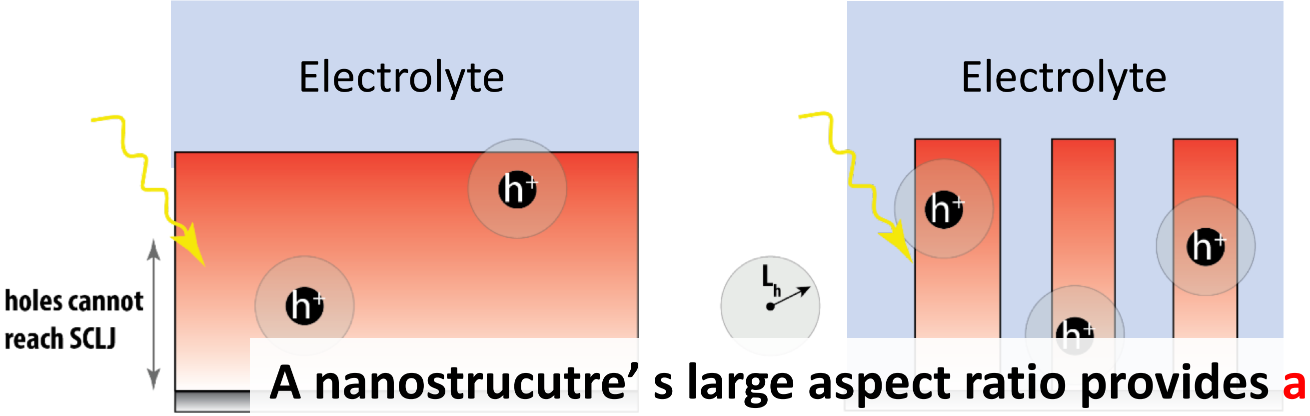


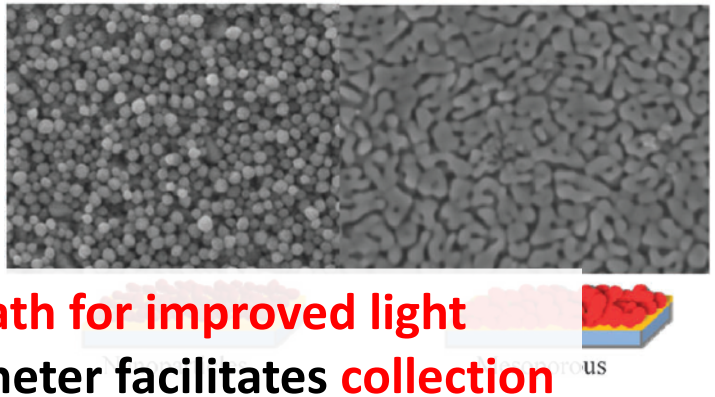




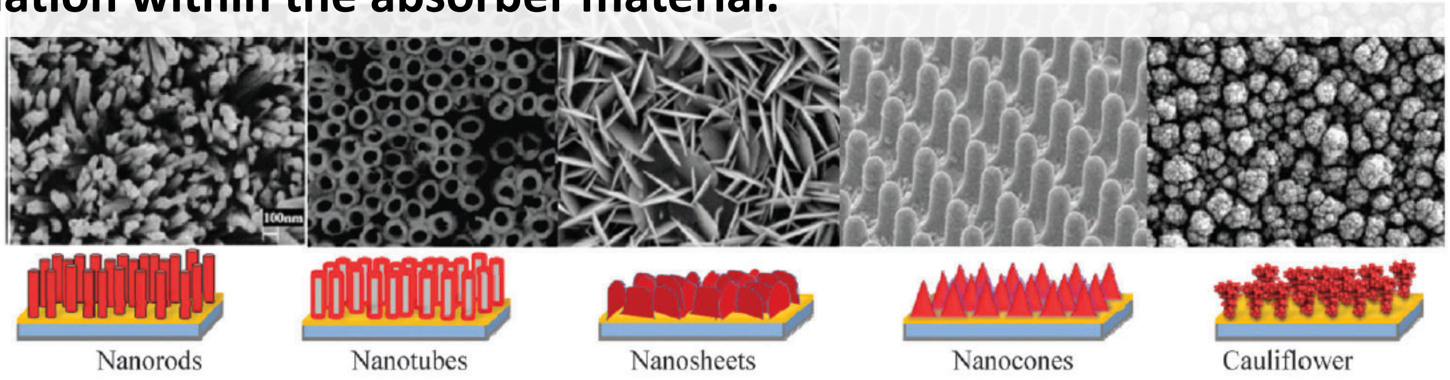
A. G. Tamirat et al., *Nanoscale Horiz.*, **1**, 243 (2016)

Bulk Problems in α-Fe_2O_3 (hematite)



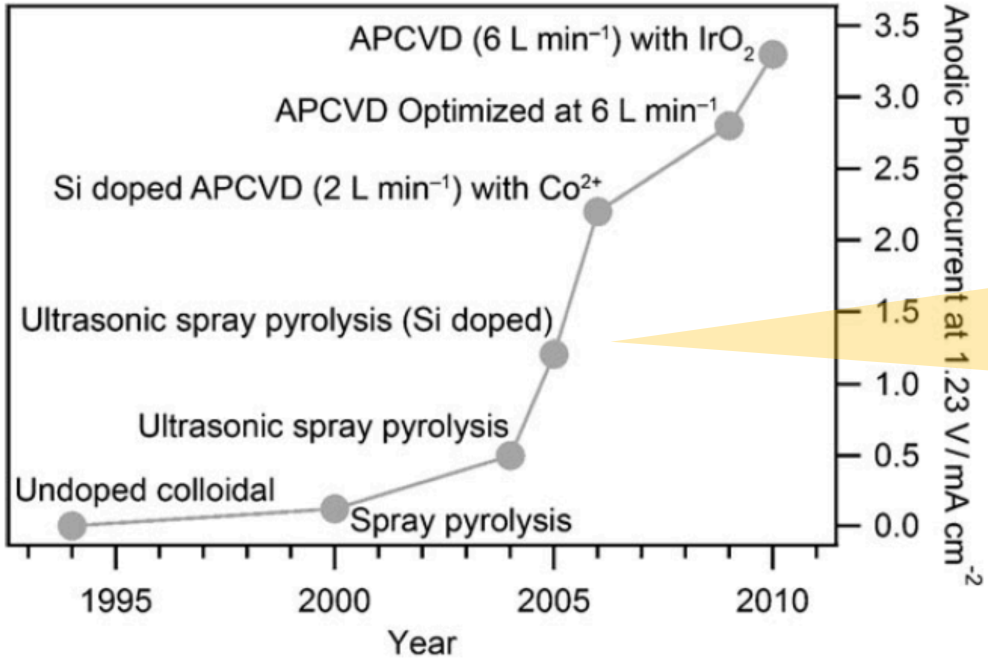


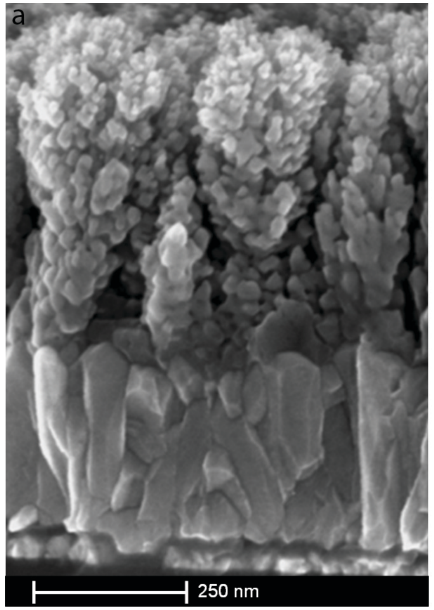
A nanostrucutre’ s large aspect ratio provides **a long optical path for improved light absorption along the vertical axis**, while its much smaller diameter facilitates **collection of minority carriers over a shorter distance**, minimizing the probability of recombination within the absorber material.



A. G. Tamirat et al., *Nanoscale Horiz.*, **1**, 243 (2016)

Bulk Problems in α-Fe_2O_3 (hematite)





Si-doped Fe_2O_3

Substrate ($F:SnO_2$)

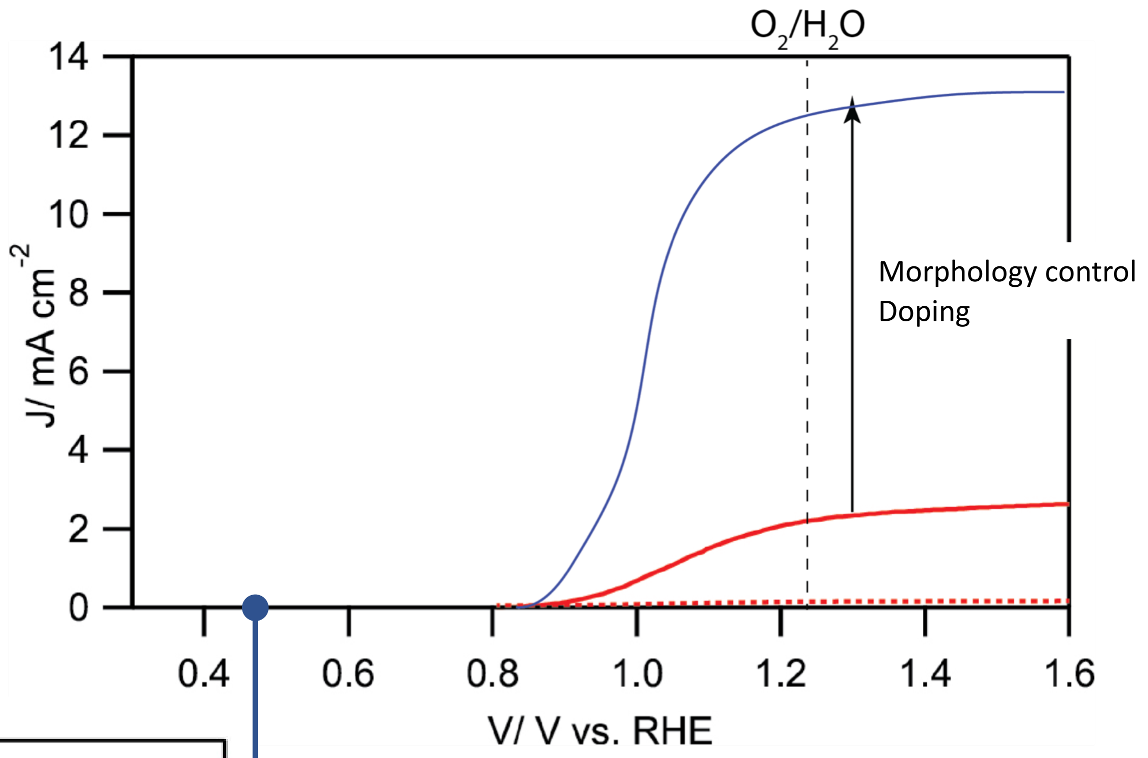
K. Sivula et al., *Chemsuschem*, **4**, 432 – 449 (2011)

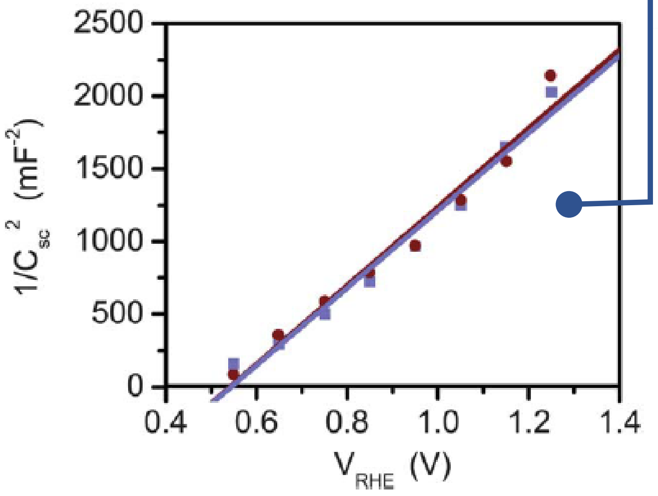
- Ti^{4+}, Sn^{4+}, Zr^{4+}, Nb^{5+} (n-type)
- Mg^{2+}, Cu^{2+} (p-type)

To promote charge transfer by increasing donor density and improve the electronic conductivity of hematite.

Ex) Zr^{4+} doped hematite: 0.1 $\Omega^{-1}cm^{-1}$ with 10^{19} cm^{-3} doping concentration

Bulk Problems in α-Fe_2O_3 (hematite)

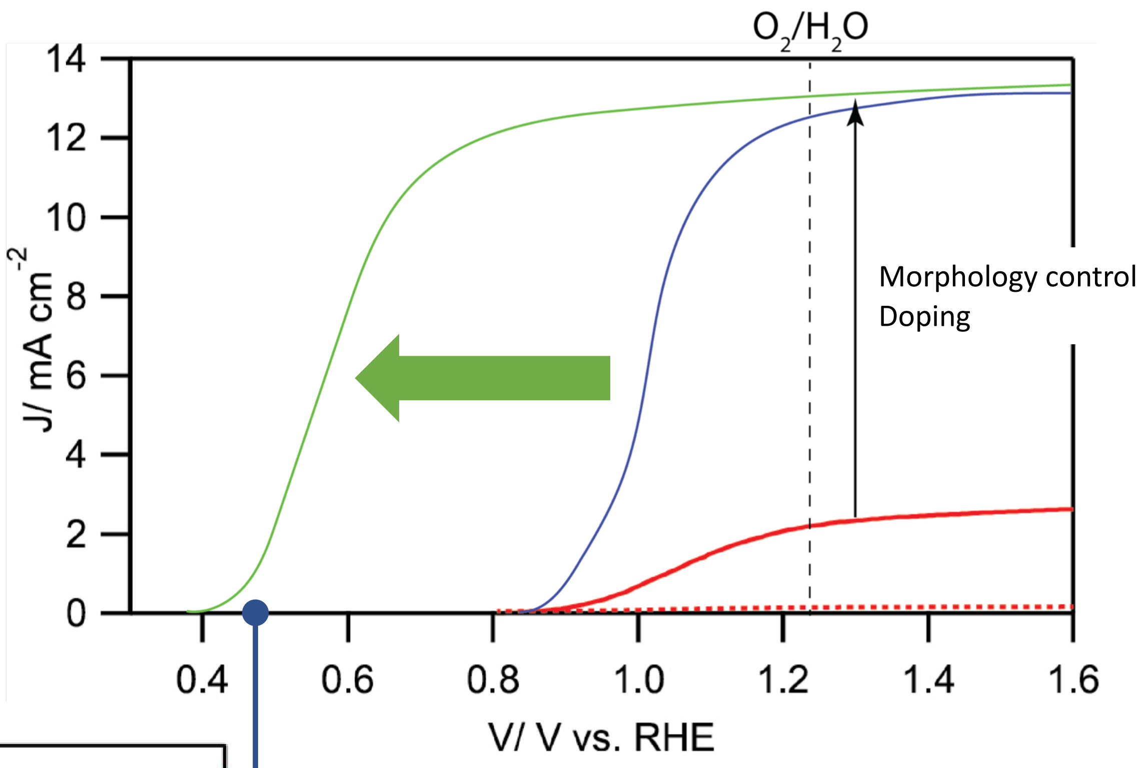


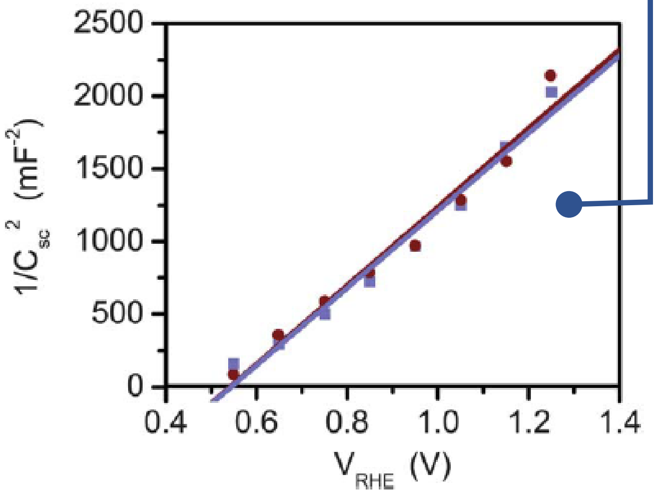


Mott-Schottky

- Jun-Ho YUM, junho.yum@epfl.ch

Bulk Problems in α-Fe_2O_3 (hematite)

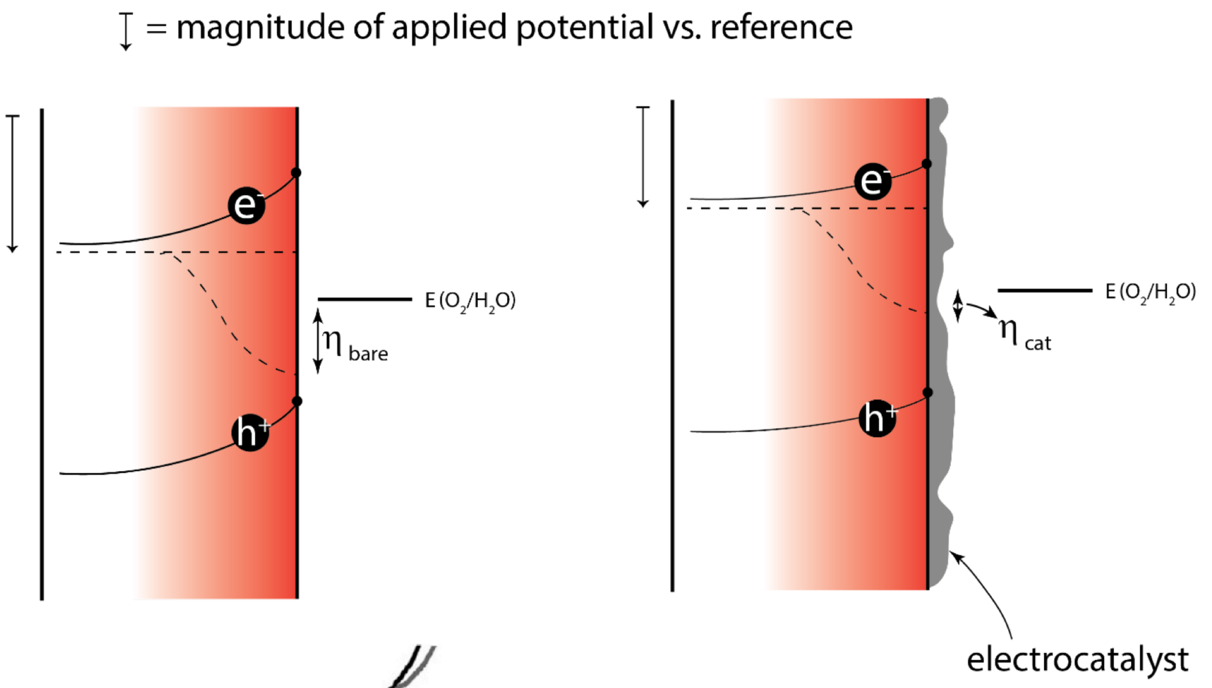


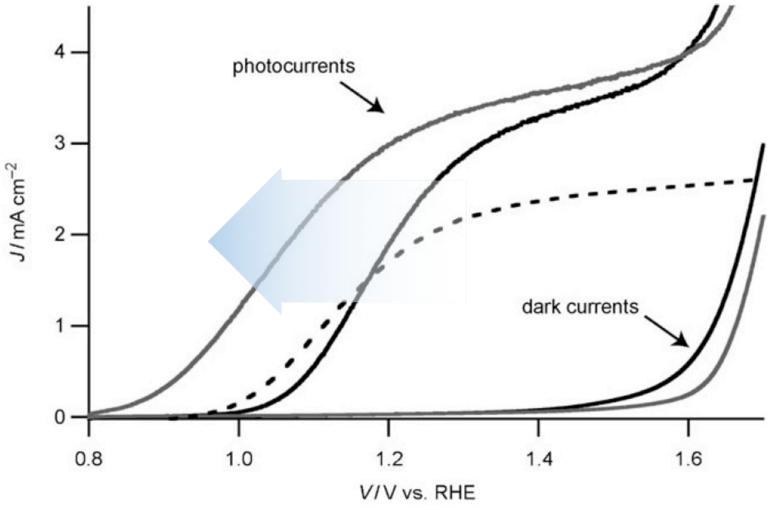


Mott-Schottky

Surface Problems in α-Fe_2O_3 (hematite) – Overpotential

Coupling with an ***electrocatalyst***



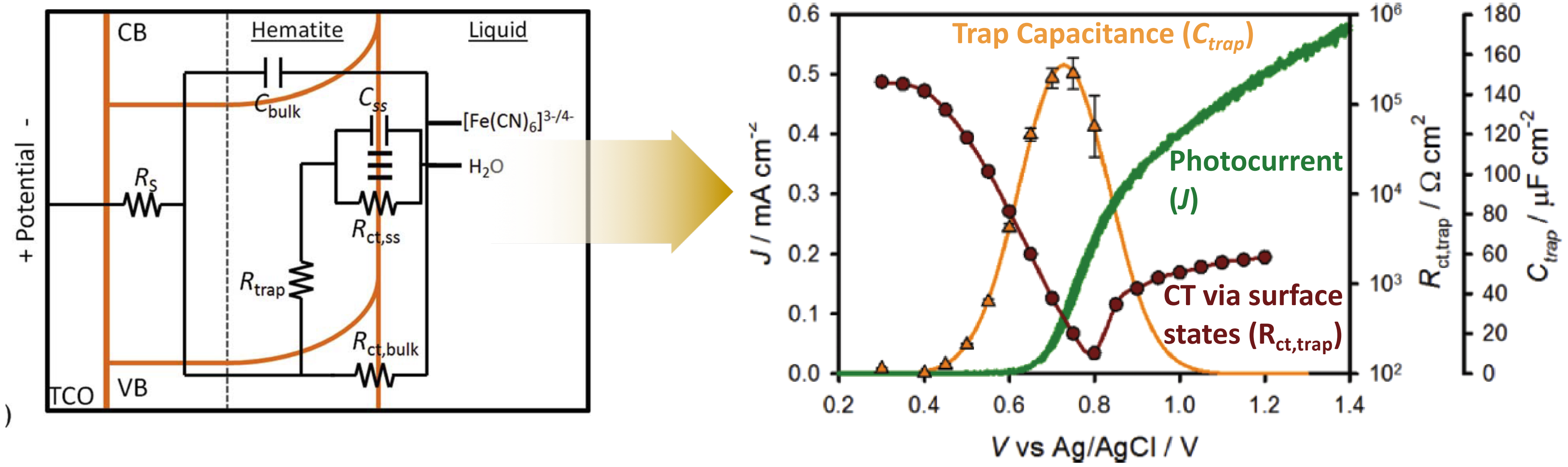


Including IrO_2 shifts slightly the V_{ON}, but still far from V_{fb}

Not only a charge transfer issue?

Surface Problems in α-Fe_2O_3 (hematite) – Overpotential

Surface recombination. *Examining the electrochemical properties of the SCLJ*

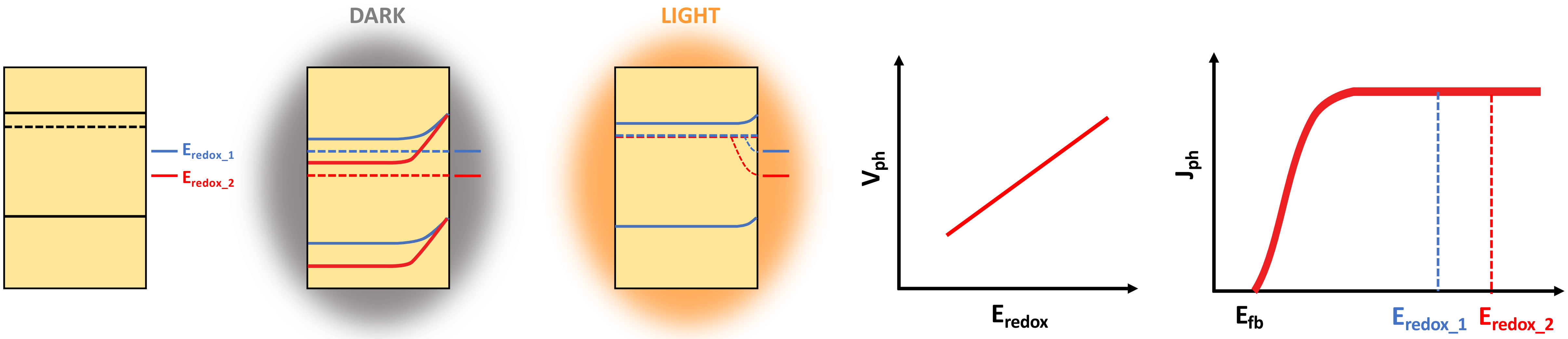


B. Klahr *et al. J. Am. Chem. Soc.*, **134**, 4294 (2012)

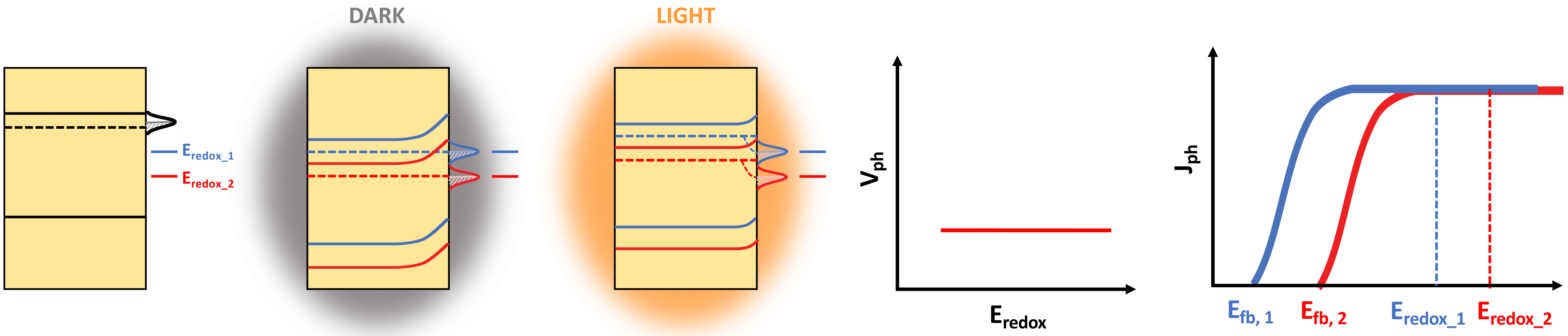
- **C_{trap}** indicate the accumulation of charges at the SCLJ just before the water oxidation starts.
- Charge transfer takes place from this surface state.
- Suggests that applying enough potential to overcome the strong surface recombination is necessary: "the delayed" onset of photocurrent is caused by Fermi Level Pinning.

Fermi Level Pinning (FLP)

No surface state / No FLP (band edge pinning)

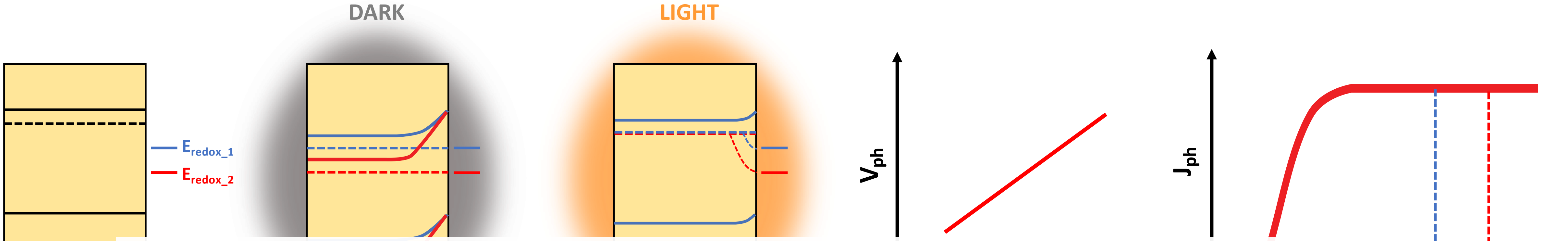


Presence of surface state/ Fermi Level Pinning



Fermi Level Pinning (FLP)

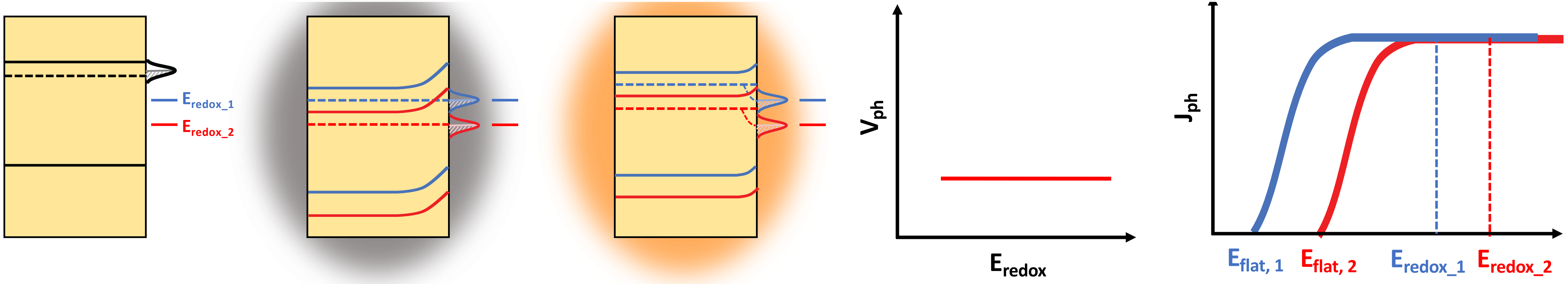
No surface state / No FLP (band edge pinning)



When the semiconductor possesses **an excess of surface states (with a density of ≈10^{13}–10^{14} cm^{-2})**, **non-negligible potential drop occurs** within the Helmholtz layer (HL), so that **band bending degree in the space charge layer is greatly weaken** and **becomes independent of the applied bias**. This effect is called **Fermi-level pinning**.

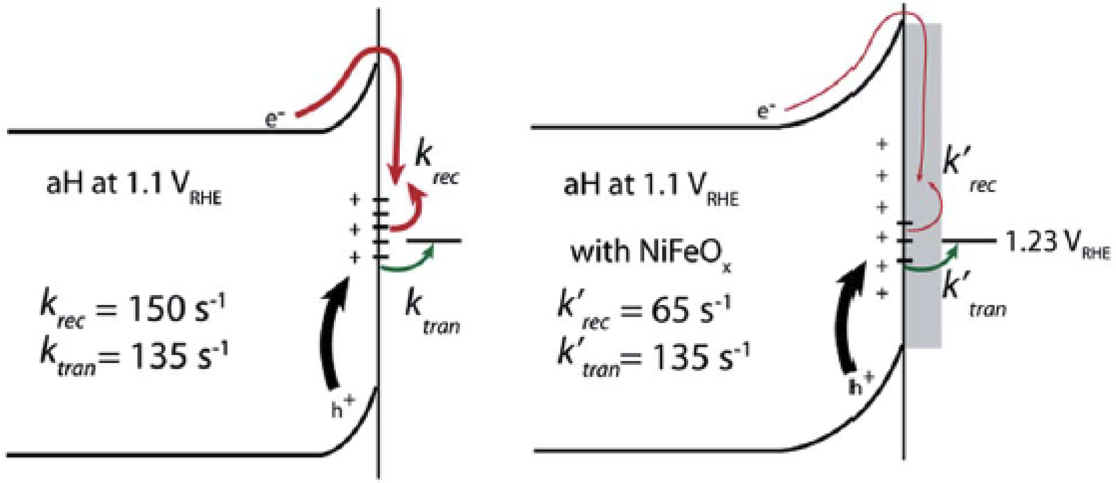
Under Fermi-level pinning conditions, the degree of band bending remains unchanged.

Presence of surface state / Fermi Level Pinning



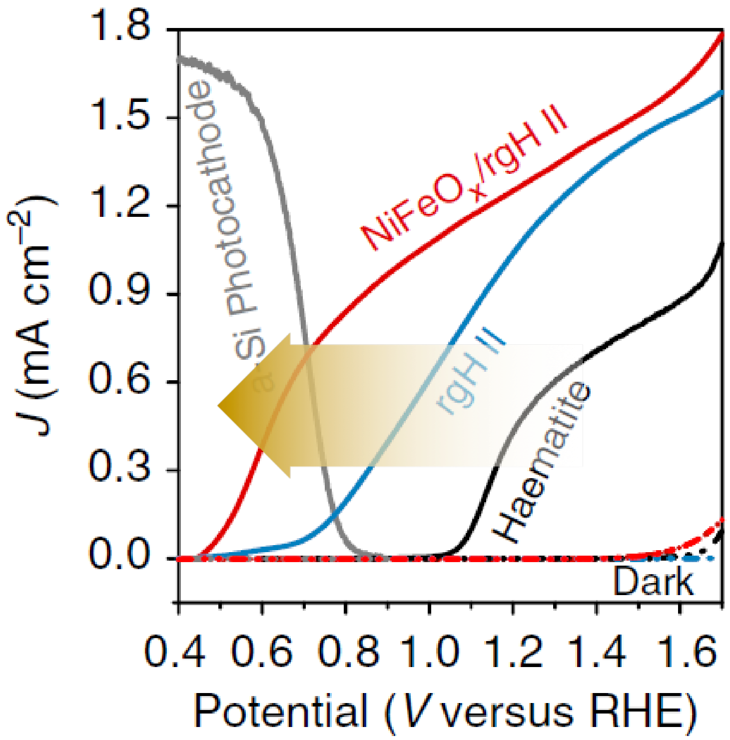
Surface Problems in α-Fe_2O_3 (hematite) – Overpotential

Surface recombination. *Examining the electrochemical properties of the SCLJ*



$NiFeO_x$ **passivate** surface traps.

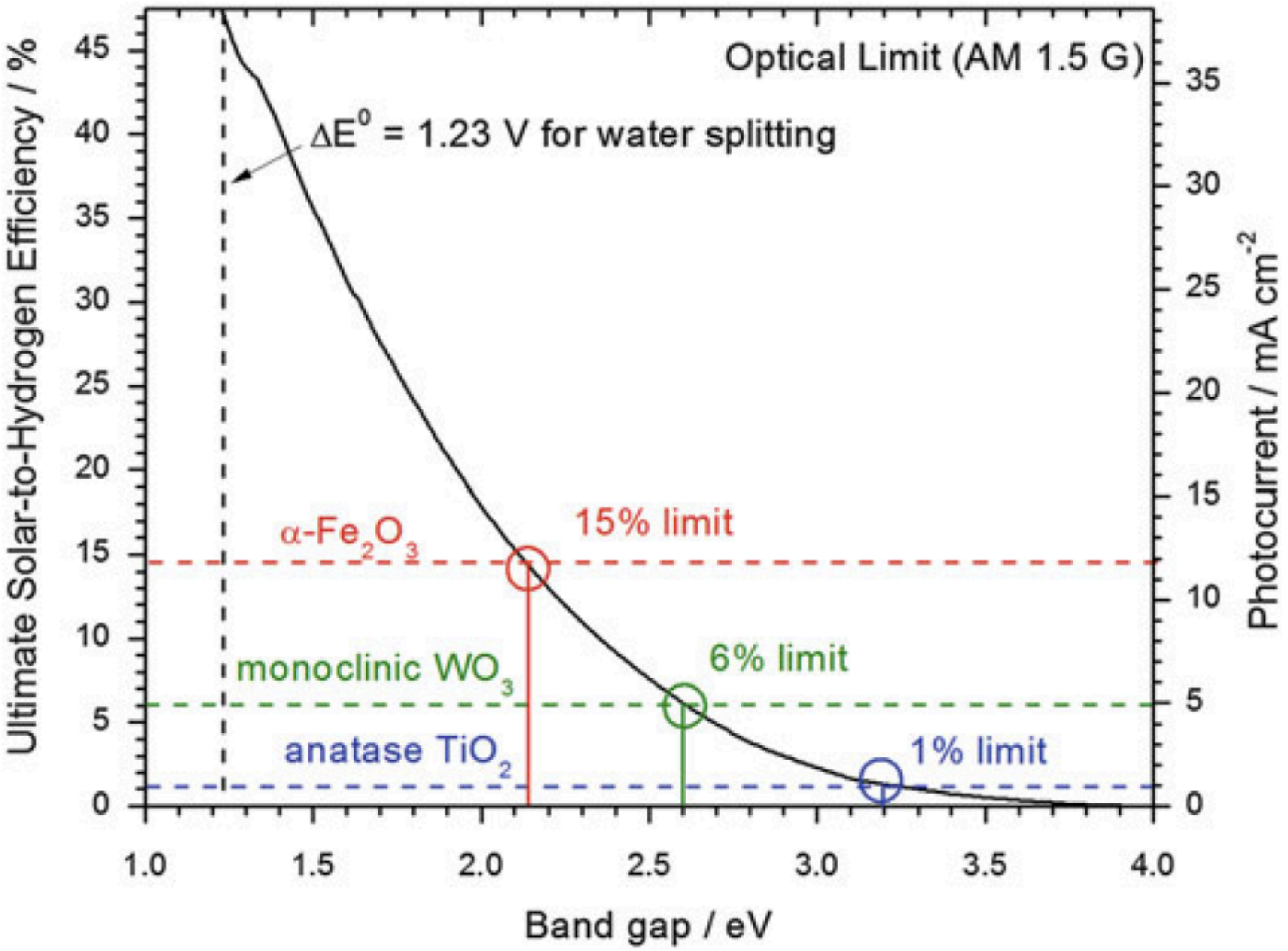
Thorne *et al. Chem. Sci.* **7**, 3347 (2016)



Deposition of $NiFeO_x$ shifts V_{on} close to V_{fb} !!!

Jang *et al. Nature Commun.* **6**, 7447 (2015)

Theoretical Maximum Solar-To-Hydrogen Efficiency



$BiVO_4$ as a potential photoanode

Advantages

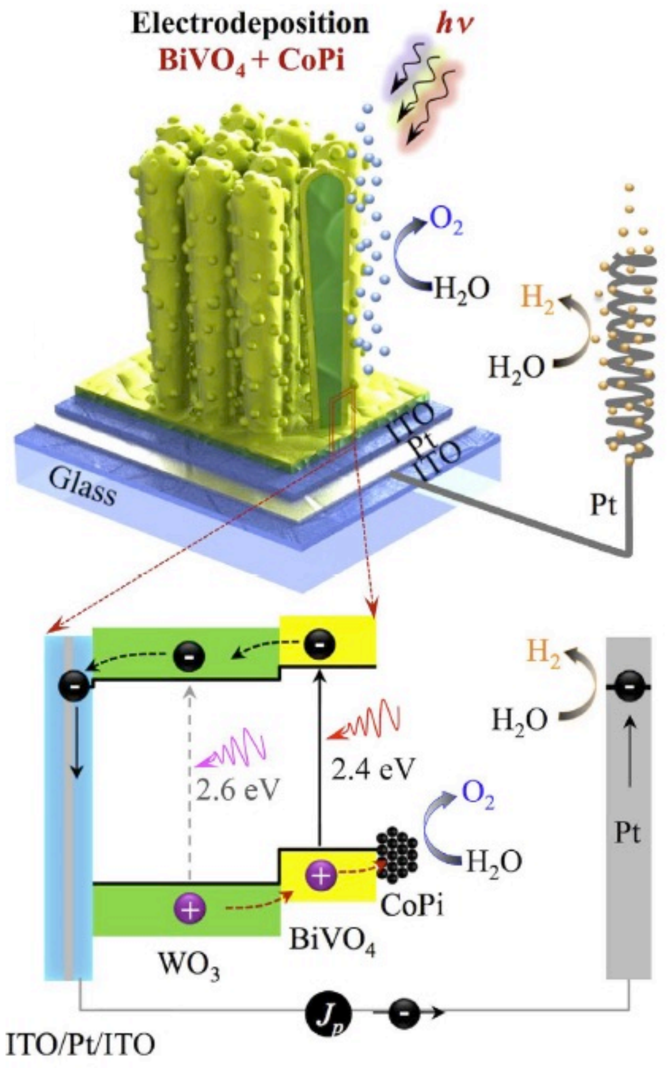
- Cheap and abundant
- Stable
- Environmentally benign
- Theoretically 7.5 mA cm^{-2} (2.5 eV)

Challenges

Bulk problems
- Short carrier diffusion length (**L_D = 70 nm**)

Surface problems
- Poor kinetics for water oxidation

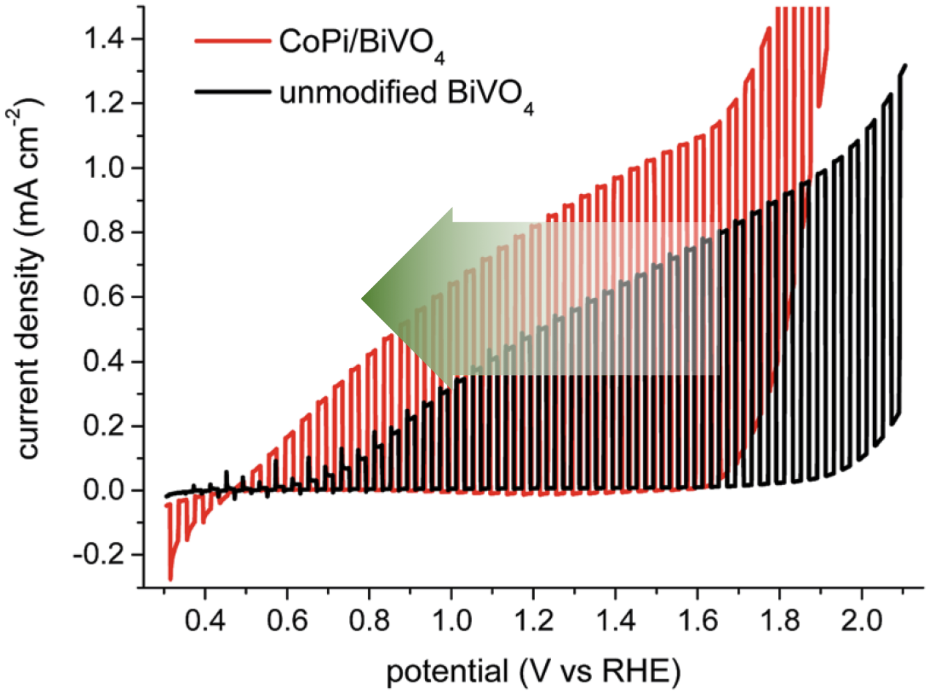
Bulk Problems in $BiVO_4$

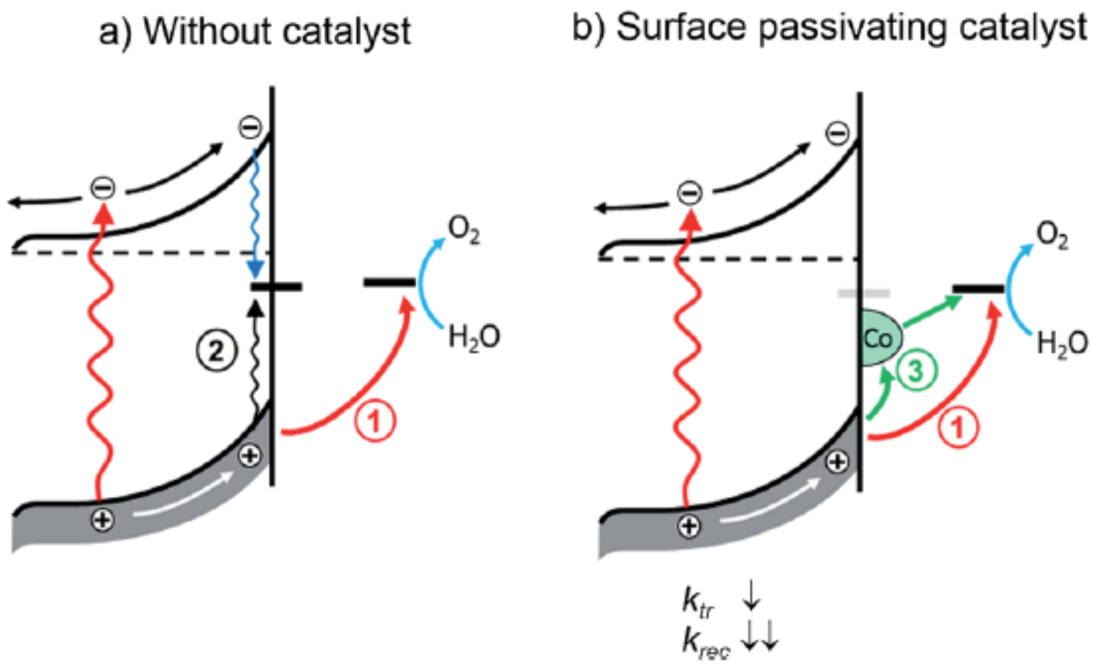


Compensate the short *L* using **extremely thin-absorber (ETA) heterojunction** structure

- $BiVO_4$ thin enough to ensure extraction of carriers
- *Nanostructure* with high-aspect ratio to ensure high light-absorption

Surface Issues in $BiVO_4$





C. Zachäus *et al. Chem. Sci.* **8**, 3712 (2017)

Deposition of CoPi (Cobalt phosphate, *co-catalyst*) enhances performance.

Analysis of carrier dynamics of photogenerated holes in $BiVO_4$ suggests that the main role of CoPi on $BiVO_4$ is not to enhance the water oxidation kinetics, but to suppress surface recombination.

Examples of Photoelectrodes

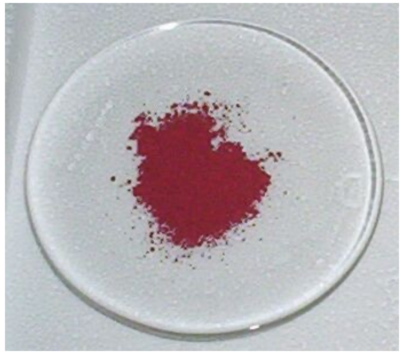
Photoanode

WO_3

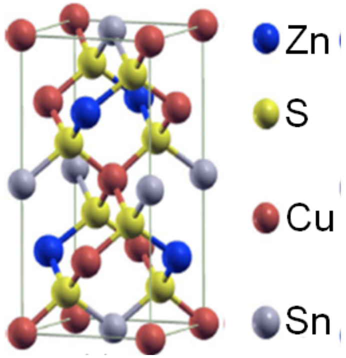
$BiVO_4$

α-Fe_2O_3

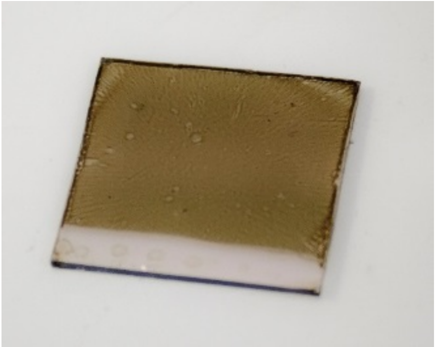
Photocathode



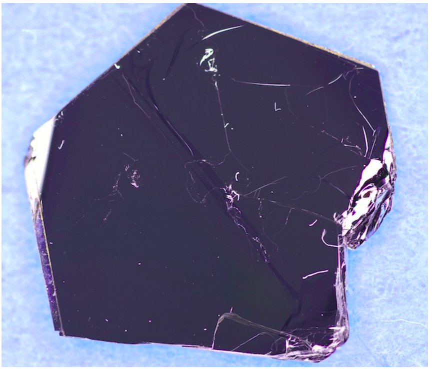
Copper(I) oxide



Cu_2ZnSnS_4

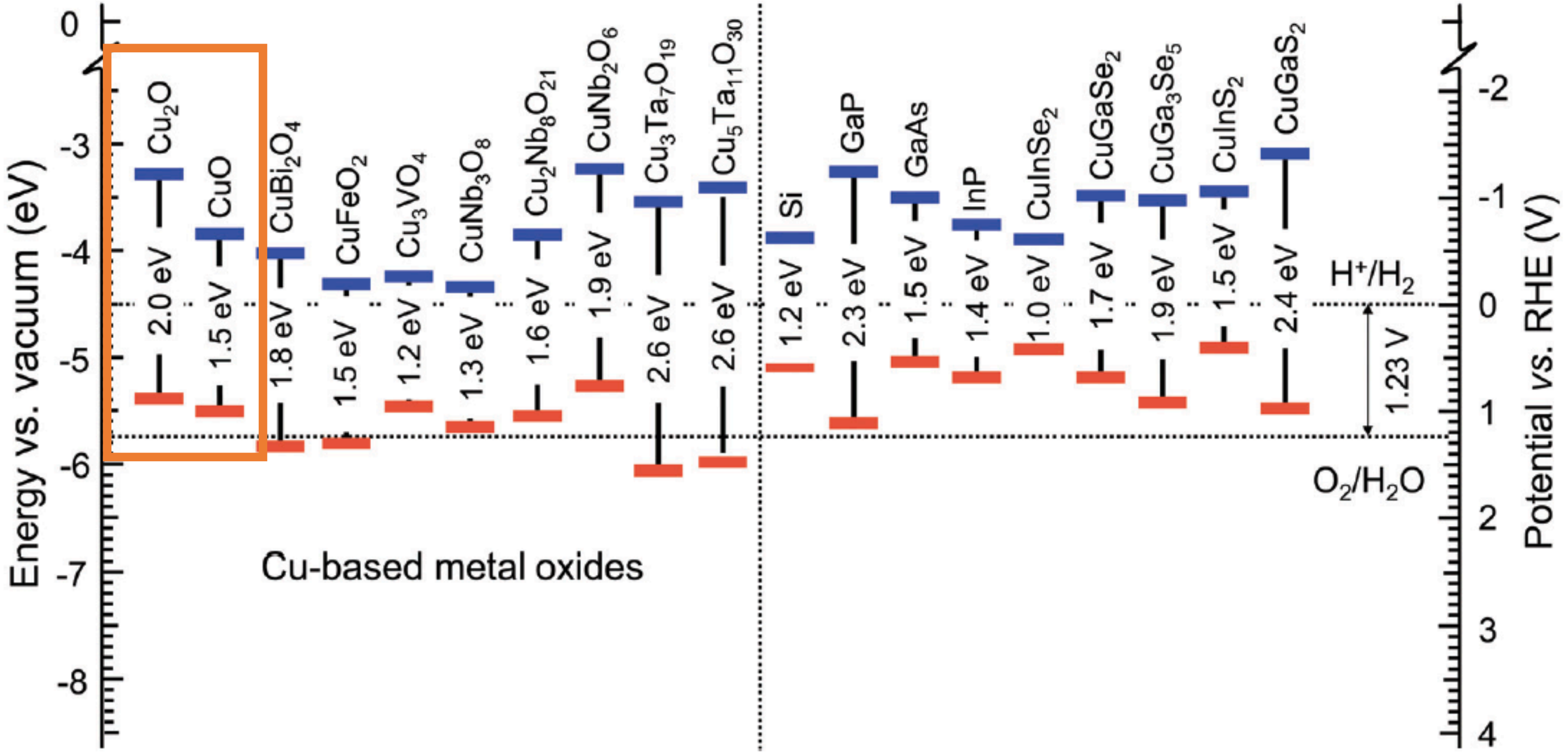


$CuFeO_2$



WSe_2

Cu based Metal Oxides



C. Li et al., *Energy Environ. Sci.*, **13**, 3269 – 3306 (2020)

Cu_2O (Cuprous oxide) as a photocathode

Advantages

- Cheap and abundant
- Environmentally benign
- Band gap 2 eV

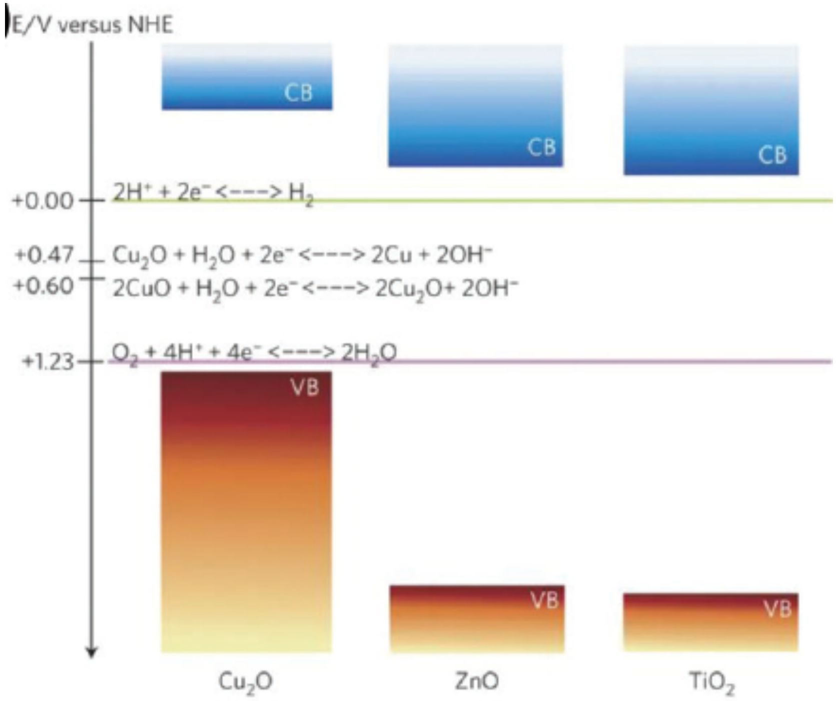
Challenges

Bulk problems

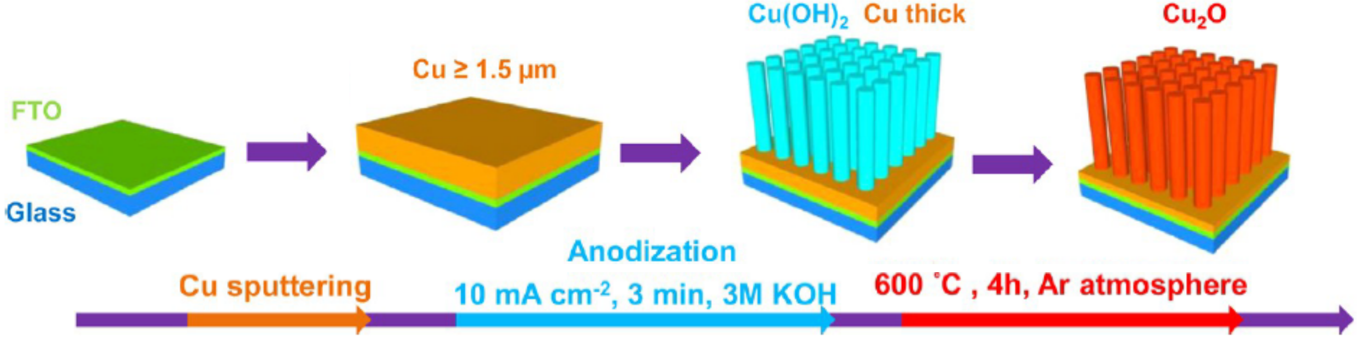
- Minority carrier diffusion length around 200 nm (light penetration depth 2.2 μm at 550 nm)

Surface problems

- Instability under operational condition (Facile reduction to Cu)

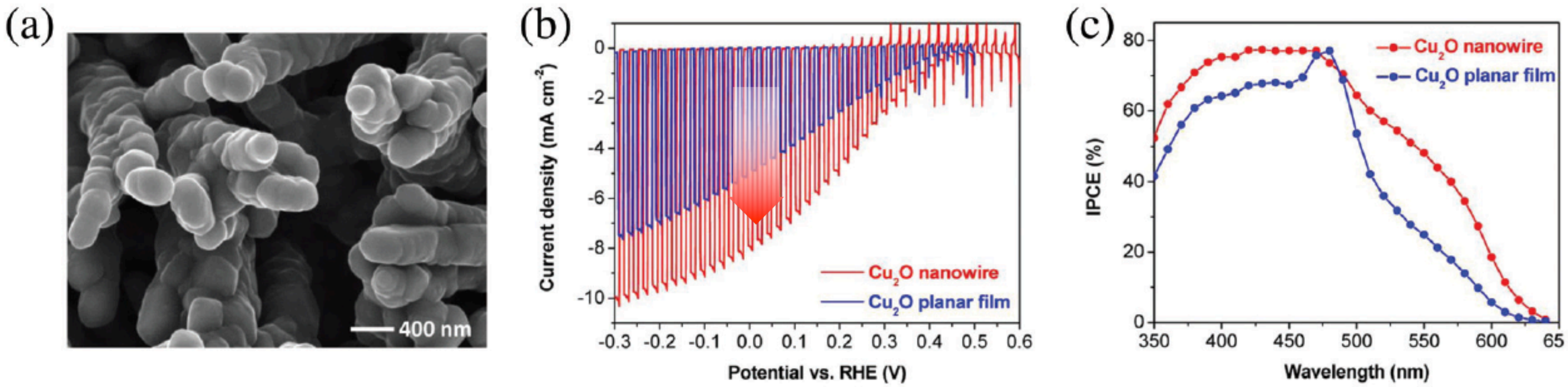


Nanostructuring Cu_2O as a photocathode



Photocathode: $Cu_2O/AZO/TiO_2/RuO_x$

- Nanowire Cu_2O
- 20 nm Al-doped ZnO/100nm TiO_2 forms a buried p-n junction
- RuO_x catalyst

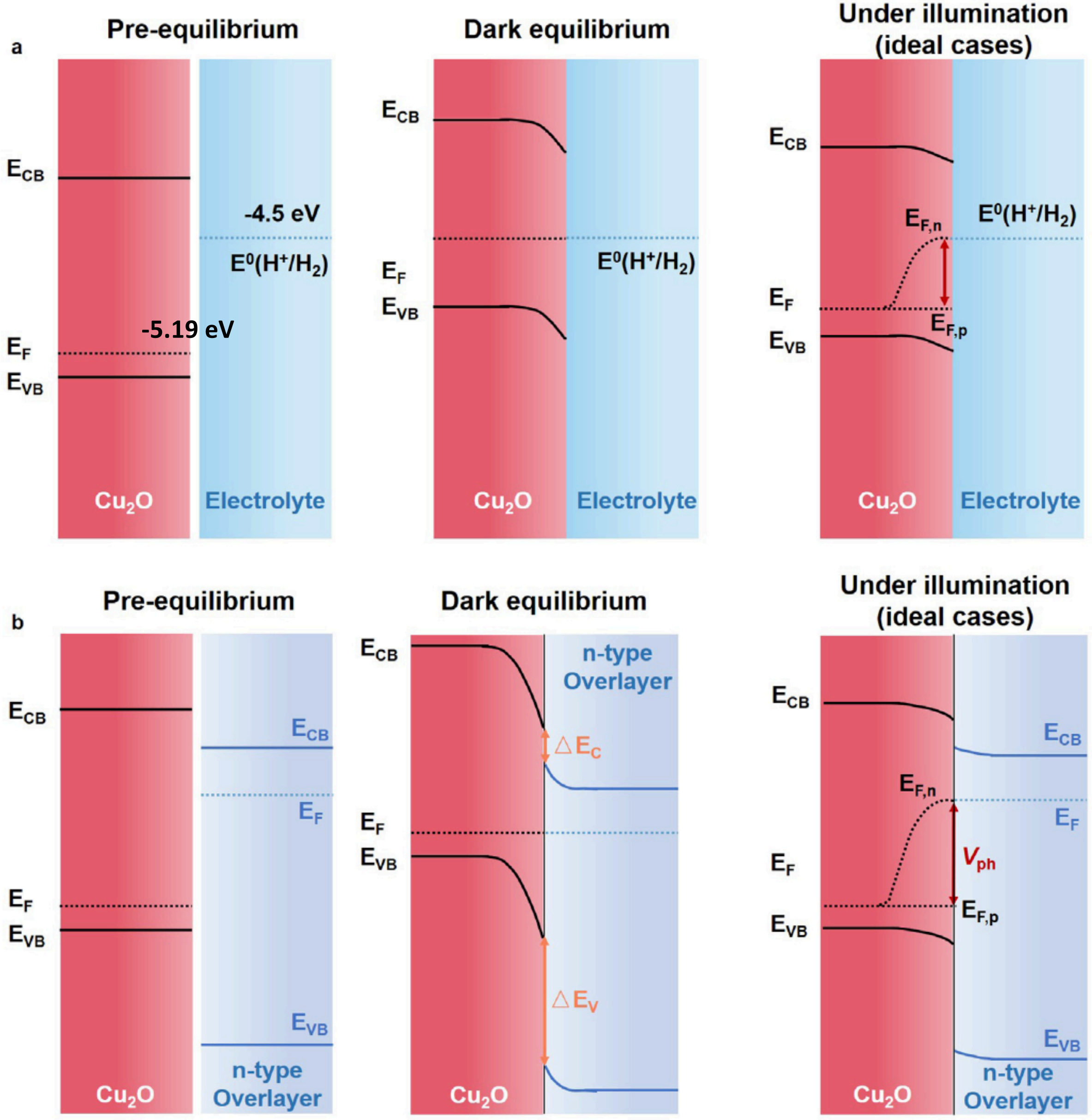


J. Luo et al., *Nano Lett.*, **16**, 1848 – 1857 (2016)

Improving the onset potential in Cu_2O photocathode

Cu_2O-liquid junction

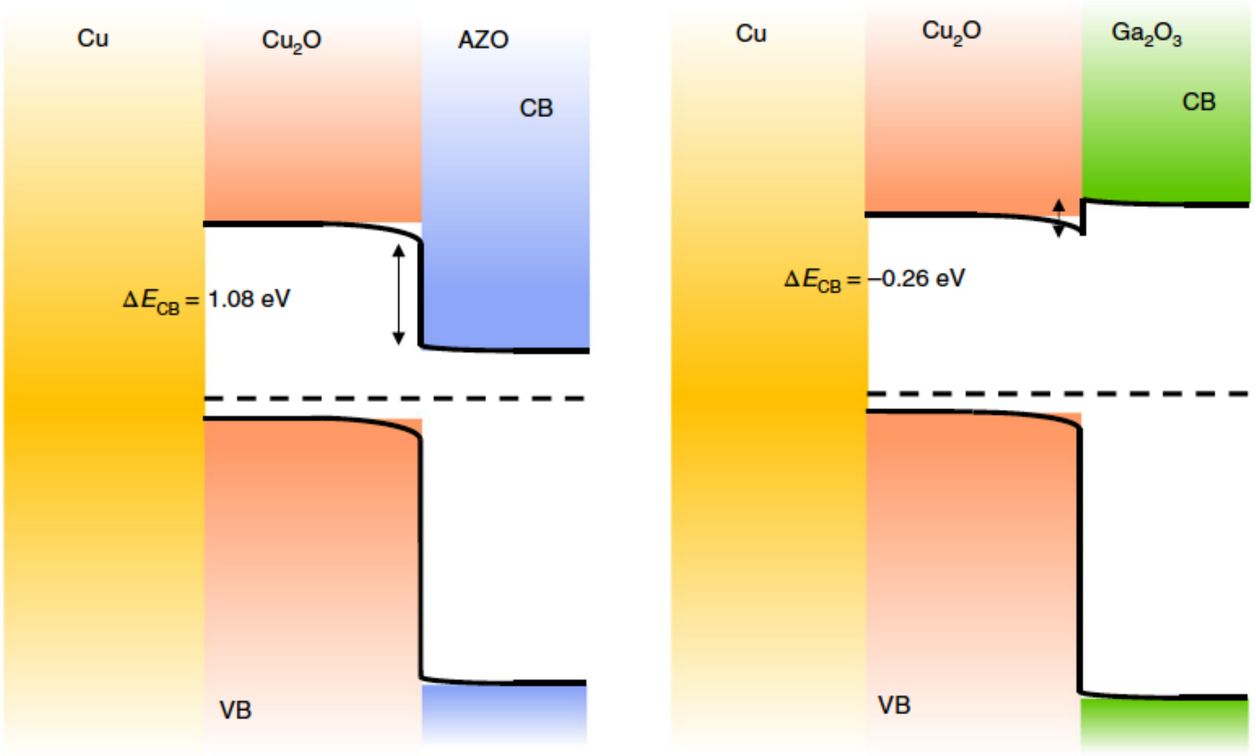
Cu_2O-n-type overlayer heterojunction (called buried junction)



- Improved photovoltage
- Passivation against photocorrosion
- Still limited photovoltage due to a large conduction band offset

J. Cheng et al., *Chem. Phys. Rev.* , **3**, 031306 (2022)

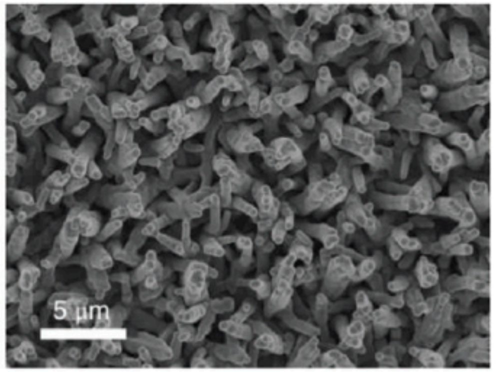
Improving the onset potential in Cu_2O photocathode



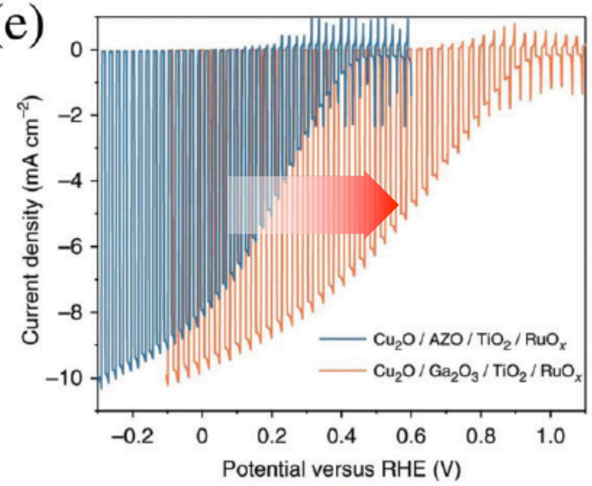
Photocathode: $Cu_2O/Ga_2O_3/TiO_2/RuO_x$

- The C.B offset between Cu_2O and Ga_2O_3 is small.
- A build-up of a large photovoltage.

(d)



(e)



L. Pan et al., *Nature Catalysis*, **1**, 412 – 420 (2018)

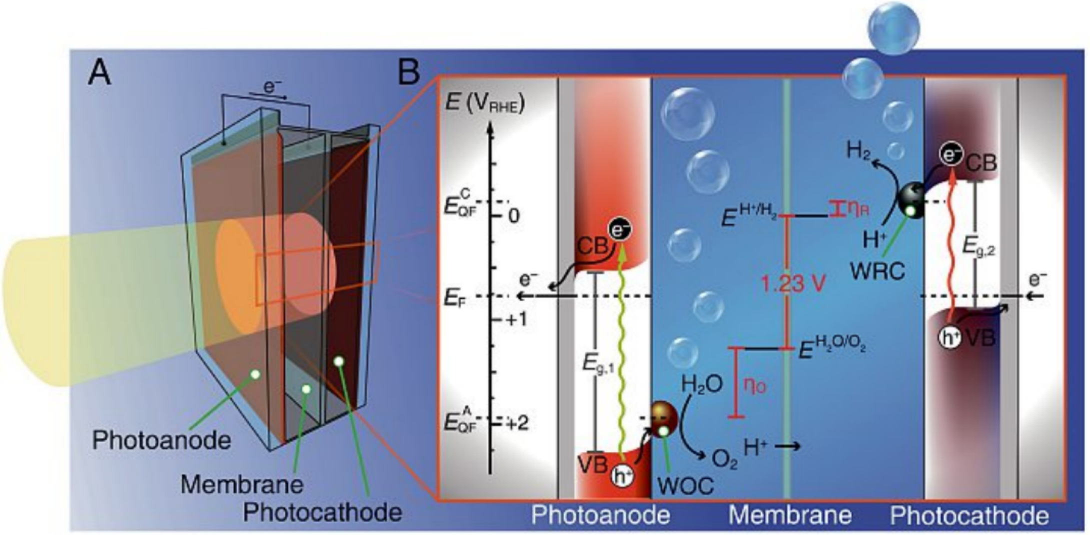
Outlook on PEC Tandem Cells

- **The formation of a SEMICONDUCTOR-LIQUID JUNCTION (SCLJ) can drive stand-alone photoelectrochemical reactions.**

- **There is still need for finding NEW MATERIALS for the design of tandem cells (complementary light absorption, robustness, excellent optoelectronic properties)**

- **Development of NOVEL STRATEGIES to effectively address issues like poor diffusion length, bulk recombination and/or surface recombination.**

An Emerging Application for Organic Semiconductors

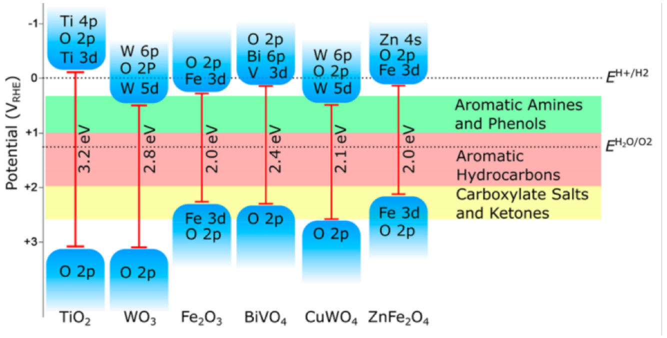


$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \quad E = 1.23 \text{ V vs RHE}$$

$$4e^- + 4H^+ \rightarrow 2H_2 \quad E = 0 \text{ V vs RHE}$$

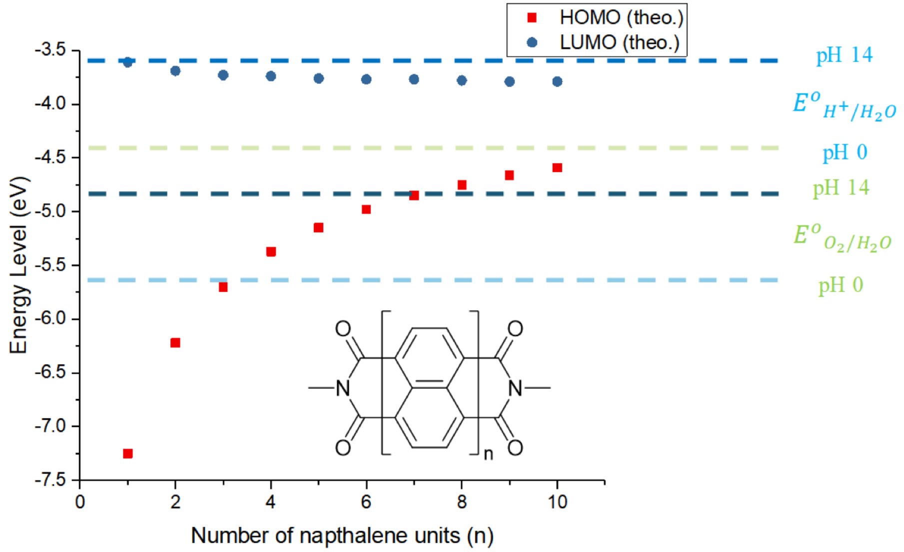
Inorganic semiconductors

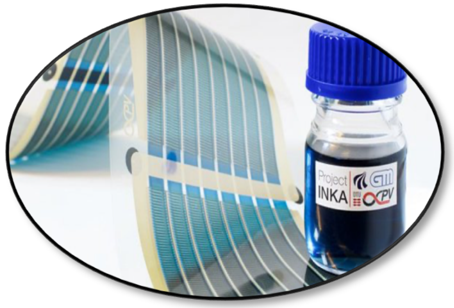
- ✓ Harsh preparation condition
- ✓ Poor charge separation
- ✓ Fixed energy level



Organic semiconductors

- ✓ Tunable energy levels
- ✓ Solution-processing & low temperature processing



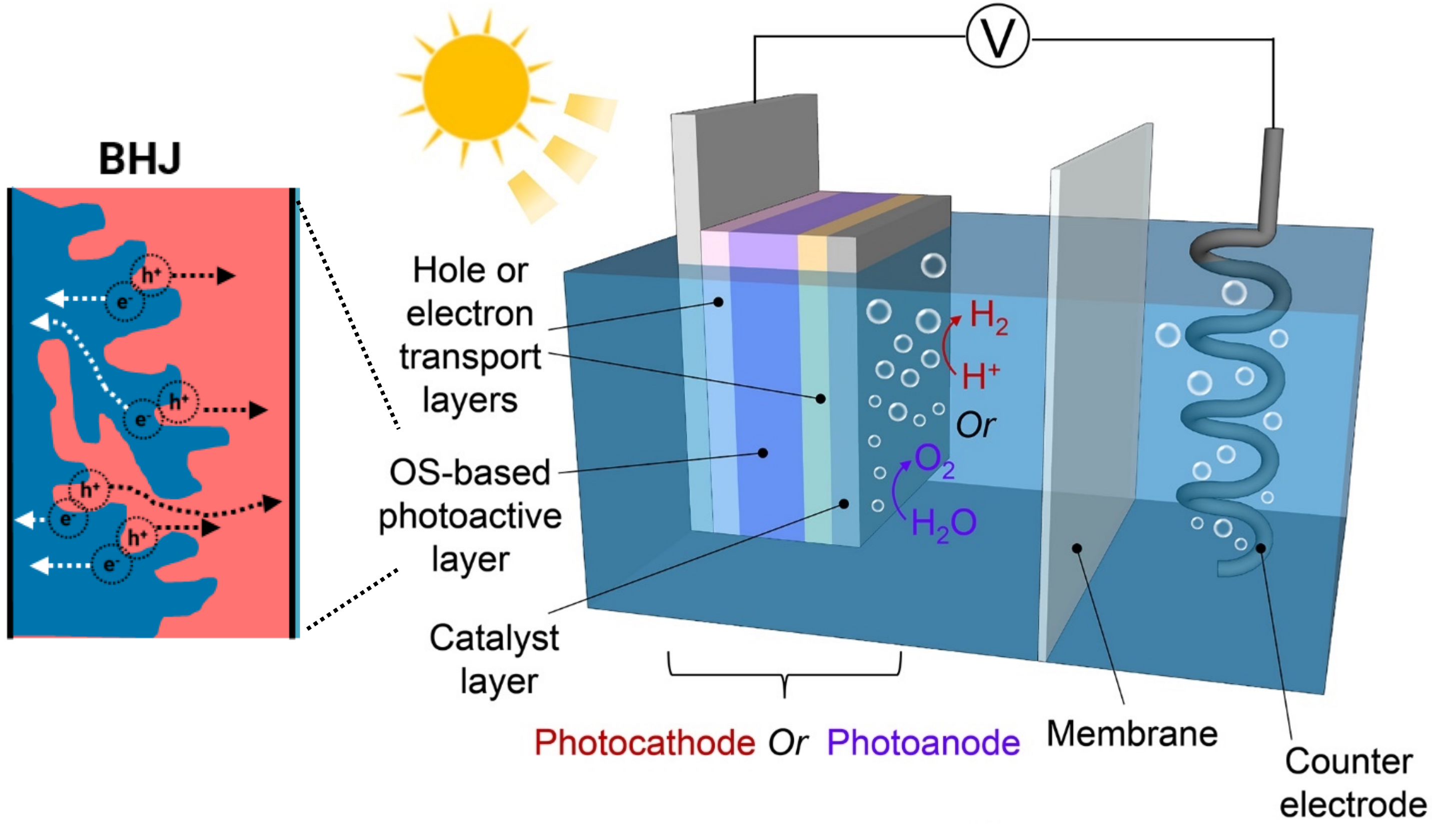


K. Sivula, *Chimia* **2017**, 71, 471-474

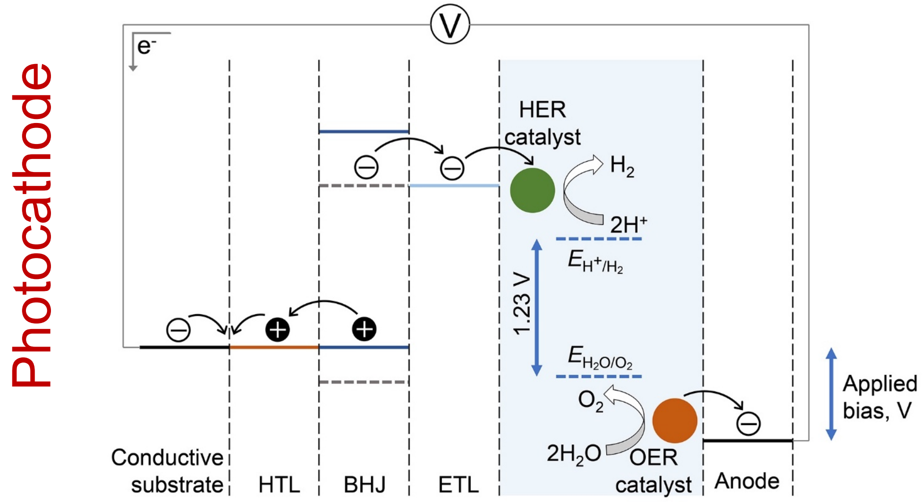
- Jun-Ho YUM, junho.yum@epfl.ch

An Emerging Application for Organic Semiconductors

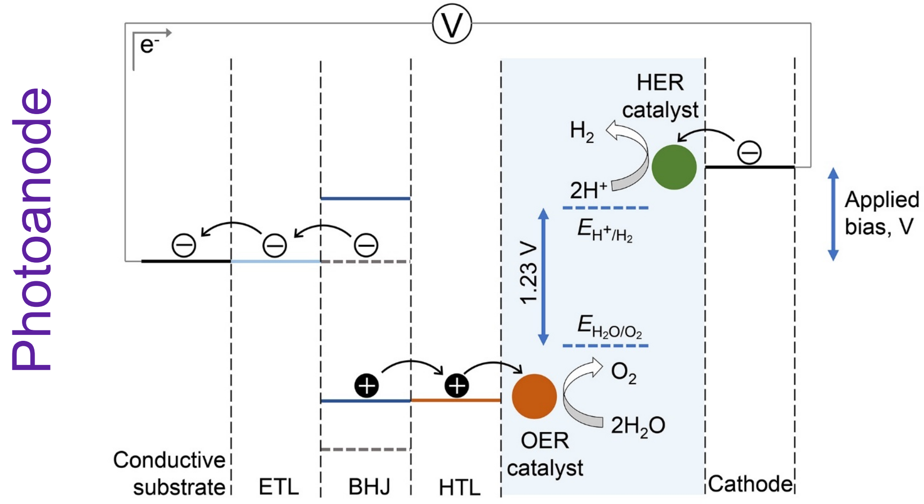
Solar-to-fuel conversion: "Artificial photosynthesis"



See review article: Yao et al. *Adv. Energy Mater.*, **2018**, *8*, 1802585.



LUMO level of Acceptor higher than H^+/H_2 potential



HOMO level of Donor lower than O_2/H_2O potential

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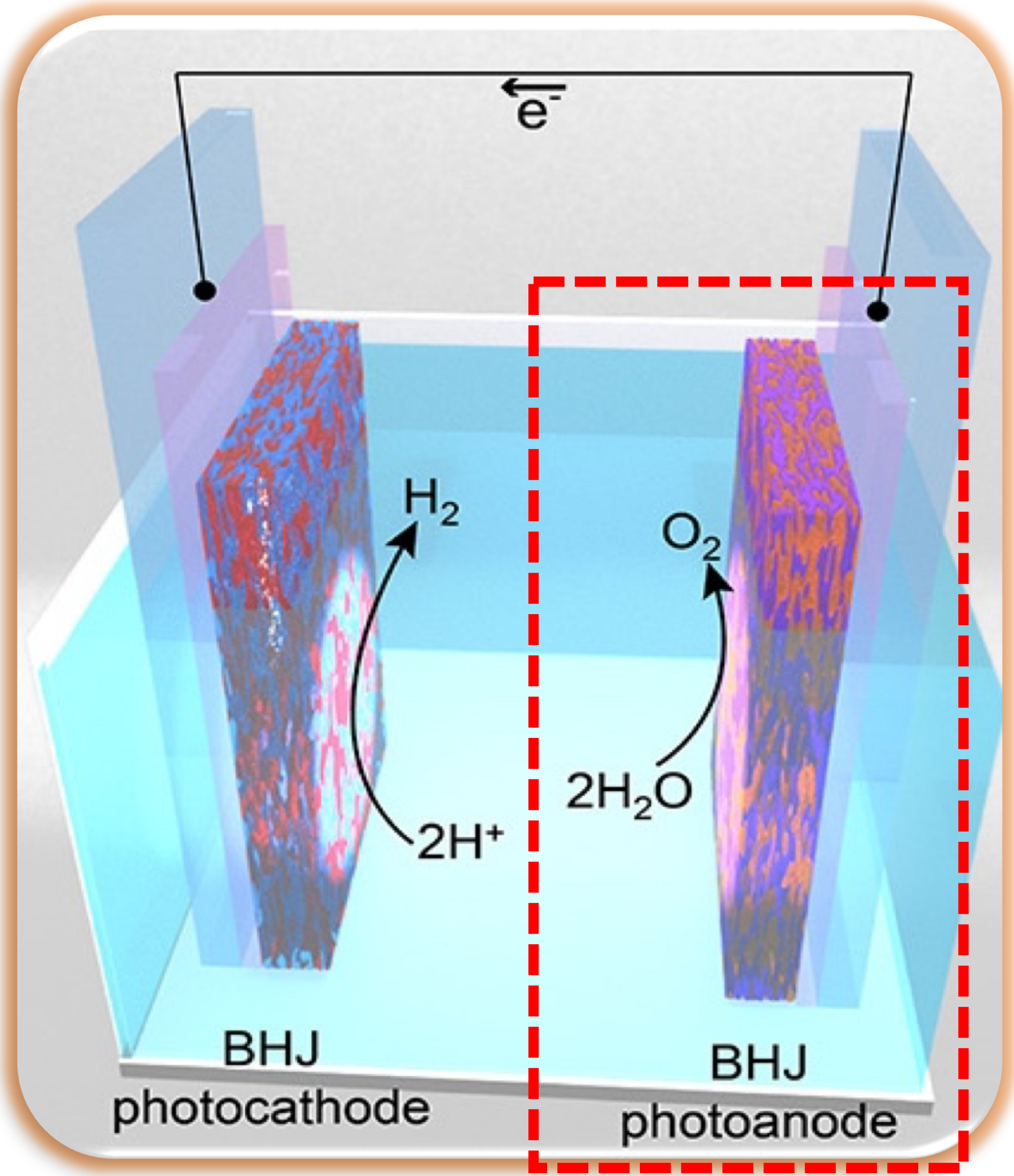
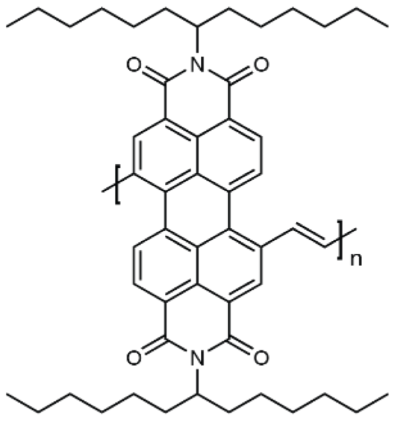
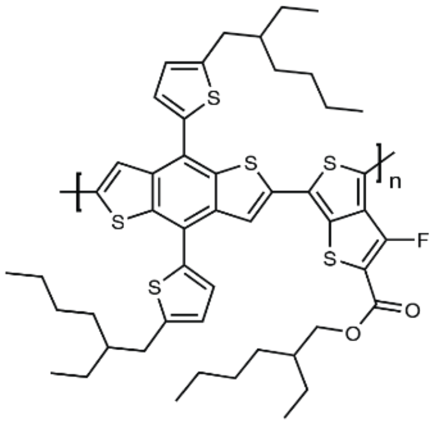
Ultimate Goal



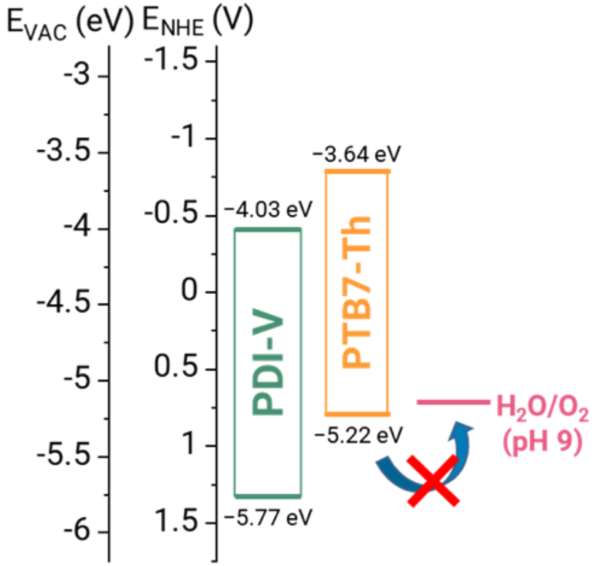
Identification of Ideal OS Materials: Photoanode

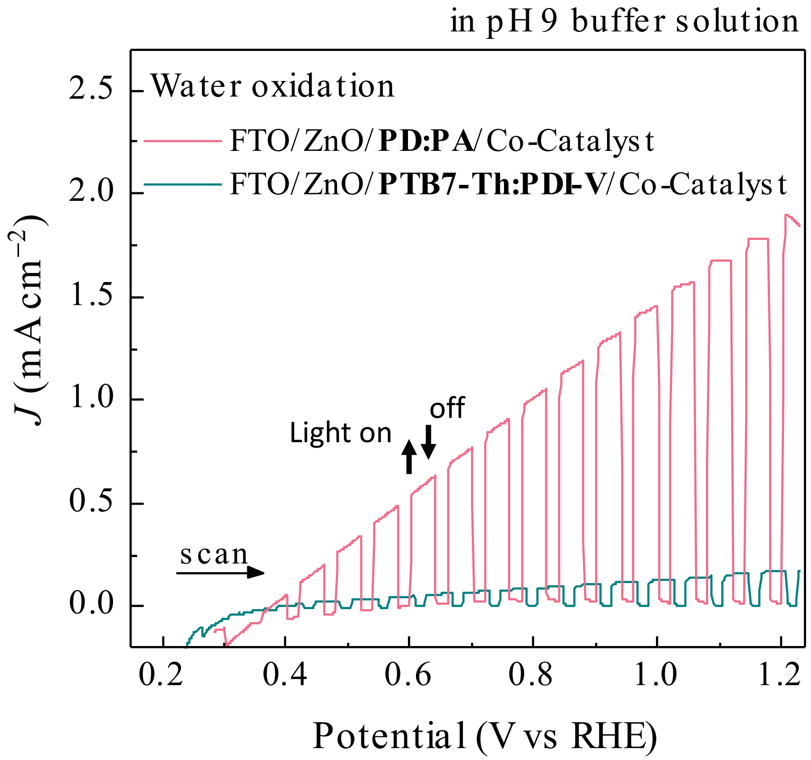


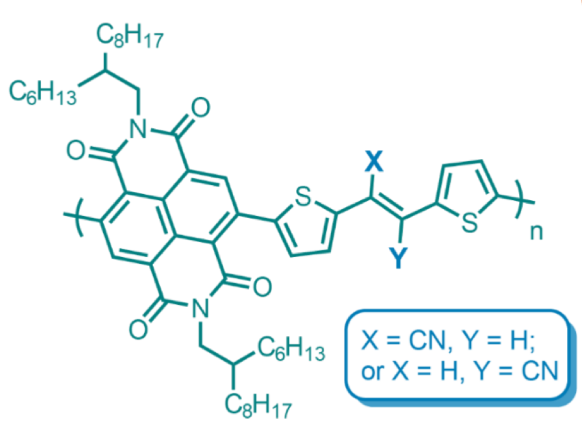
PDI-V (acceptor)



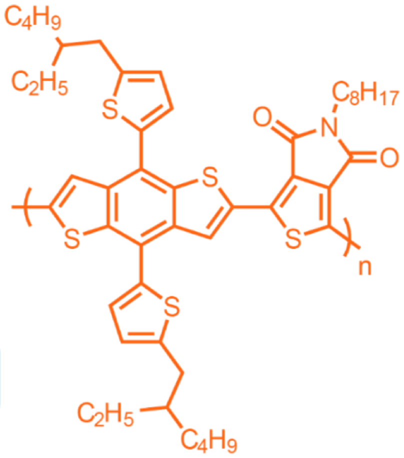
PTB7-Th (donor)



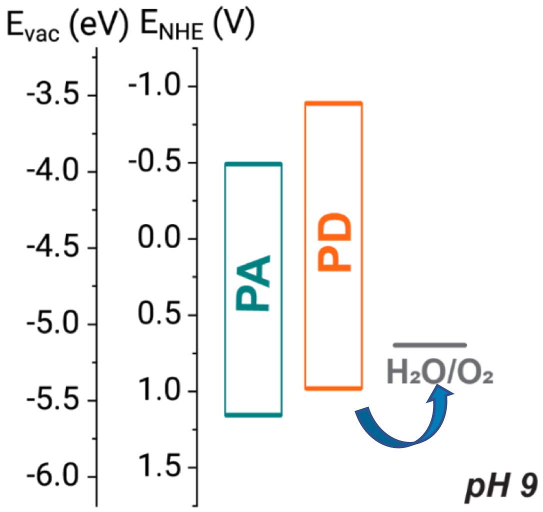




PNDITCVT (PA)

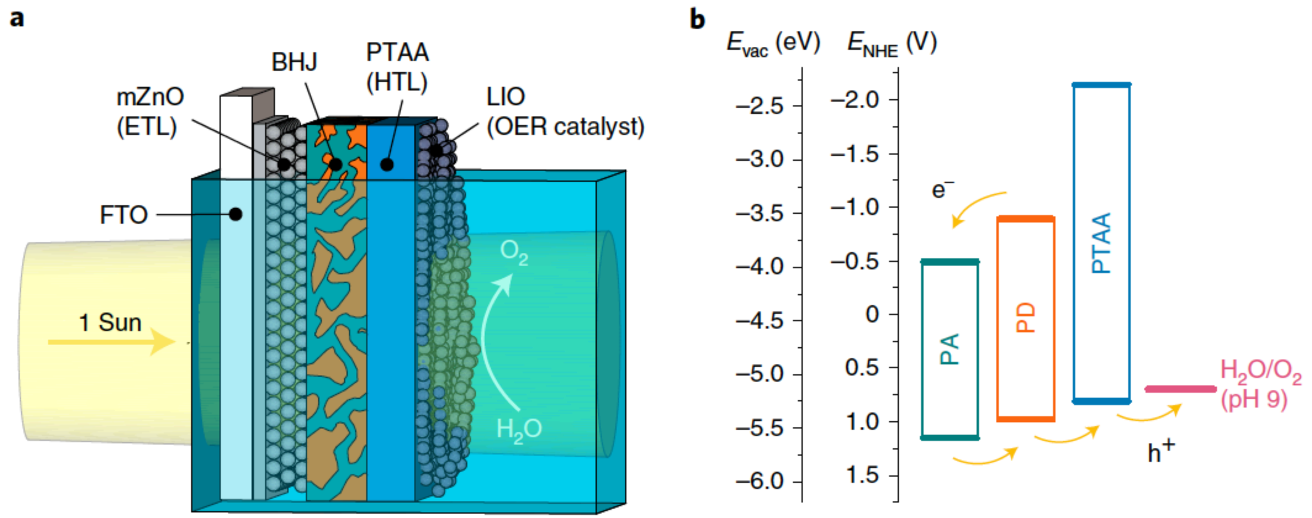


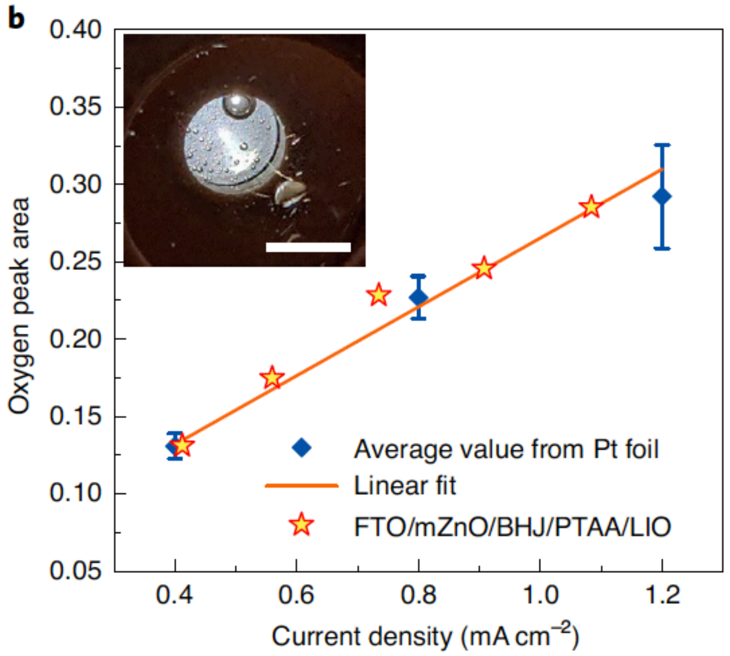
PBDTTTPD (PD)

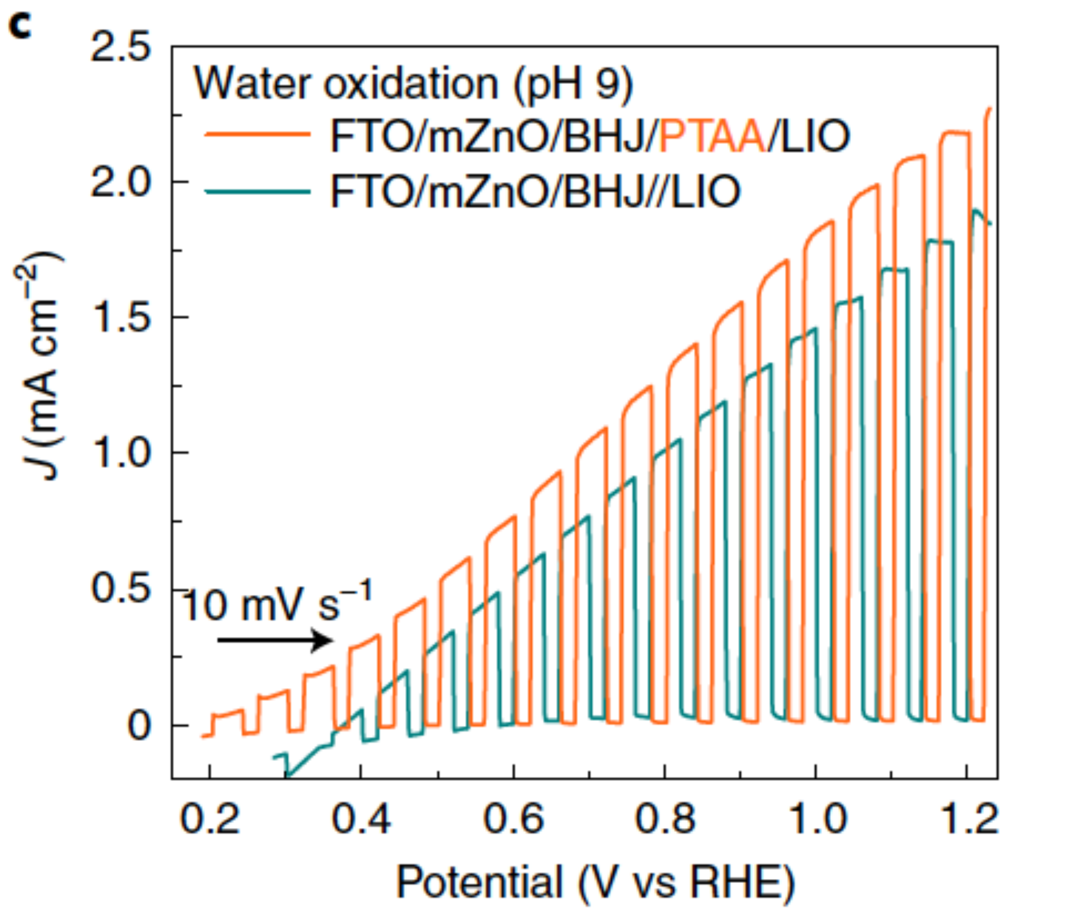


- Jun-Ho YUM, junho.yum@epfl.ch

Polymer BHJ Photoanode for Solar Water Oxidation

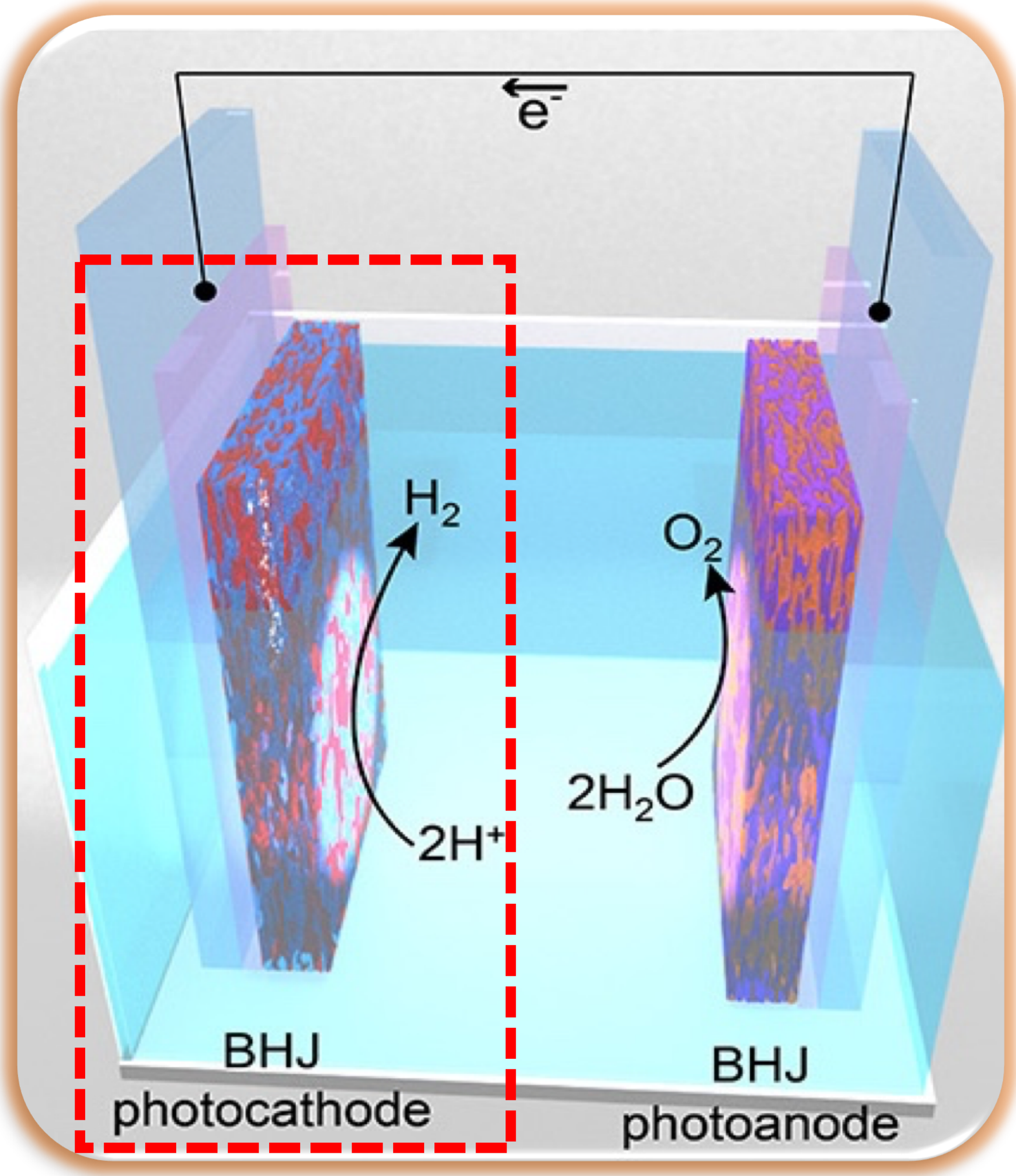




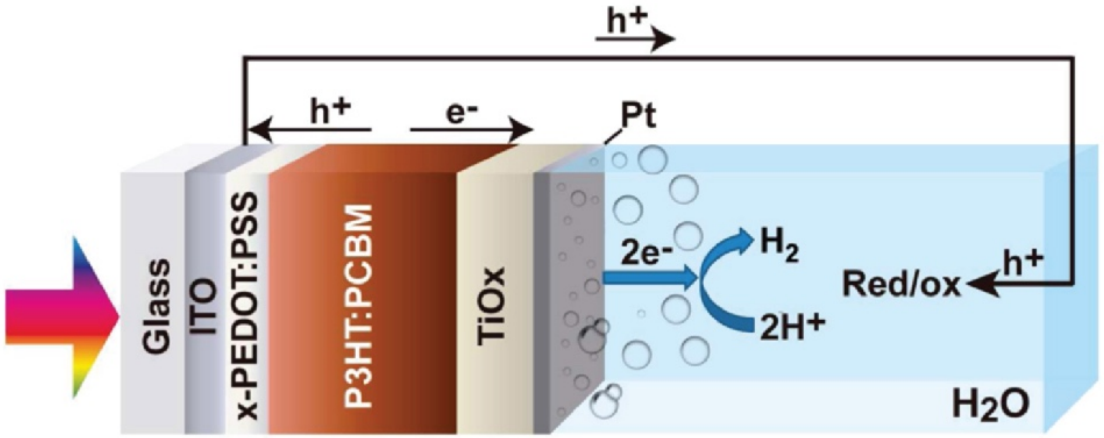


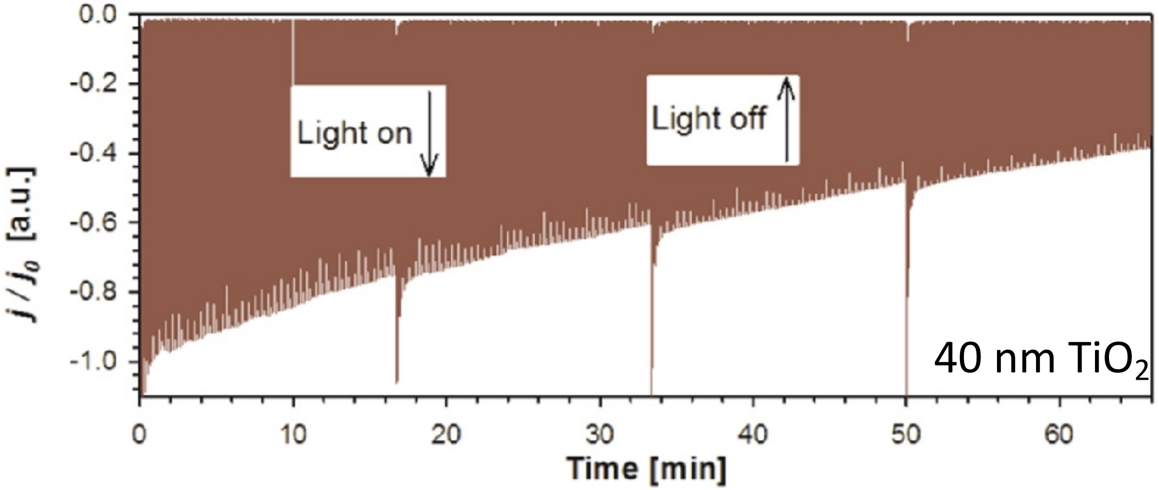
H.-H. Cho et al. *Nat. Catal.* **2021**, 4, 431–438

Ultimate Goal

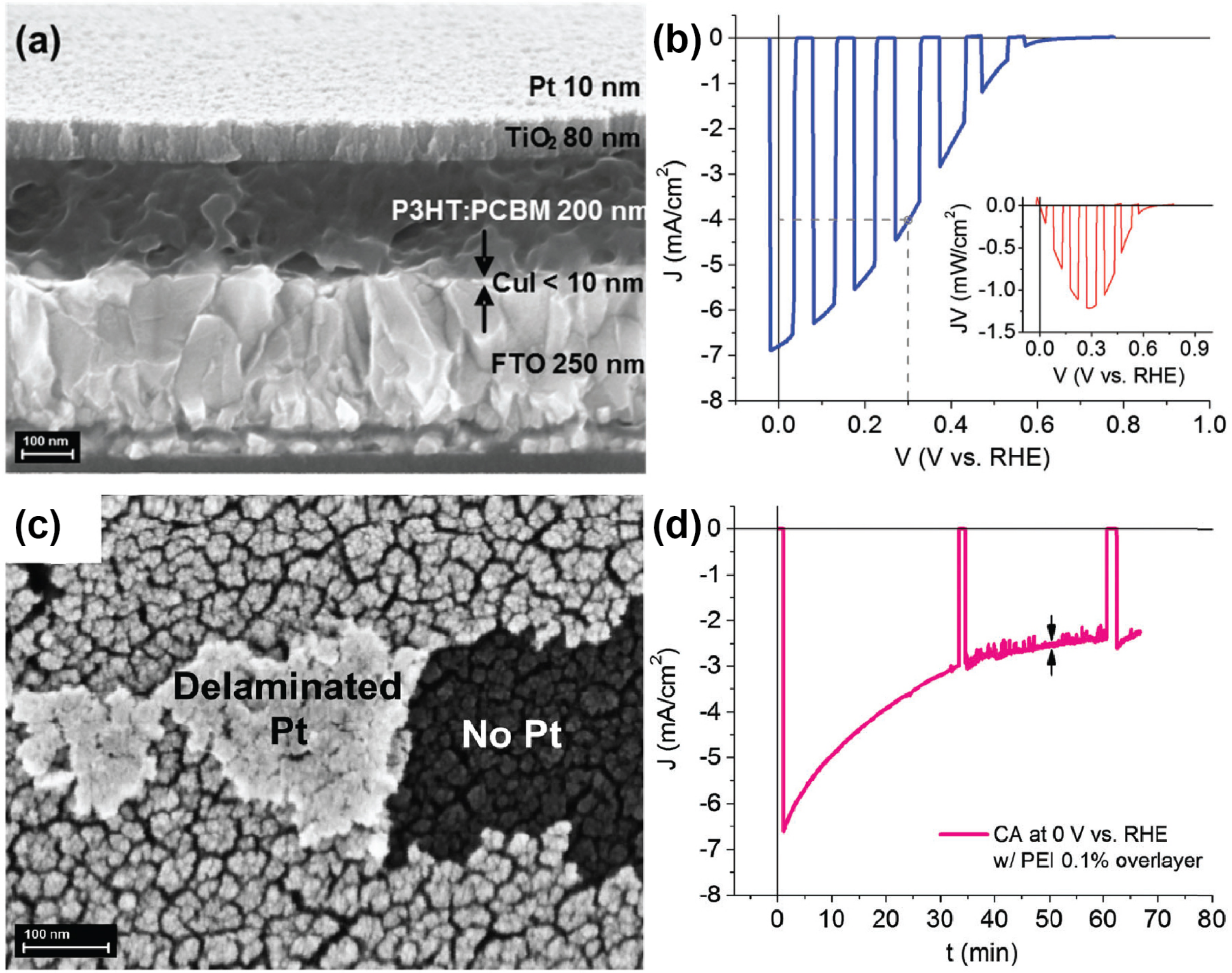


Organic semiconductor photocathodes for direct H_2 production





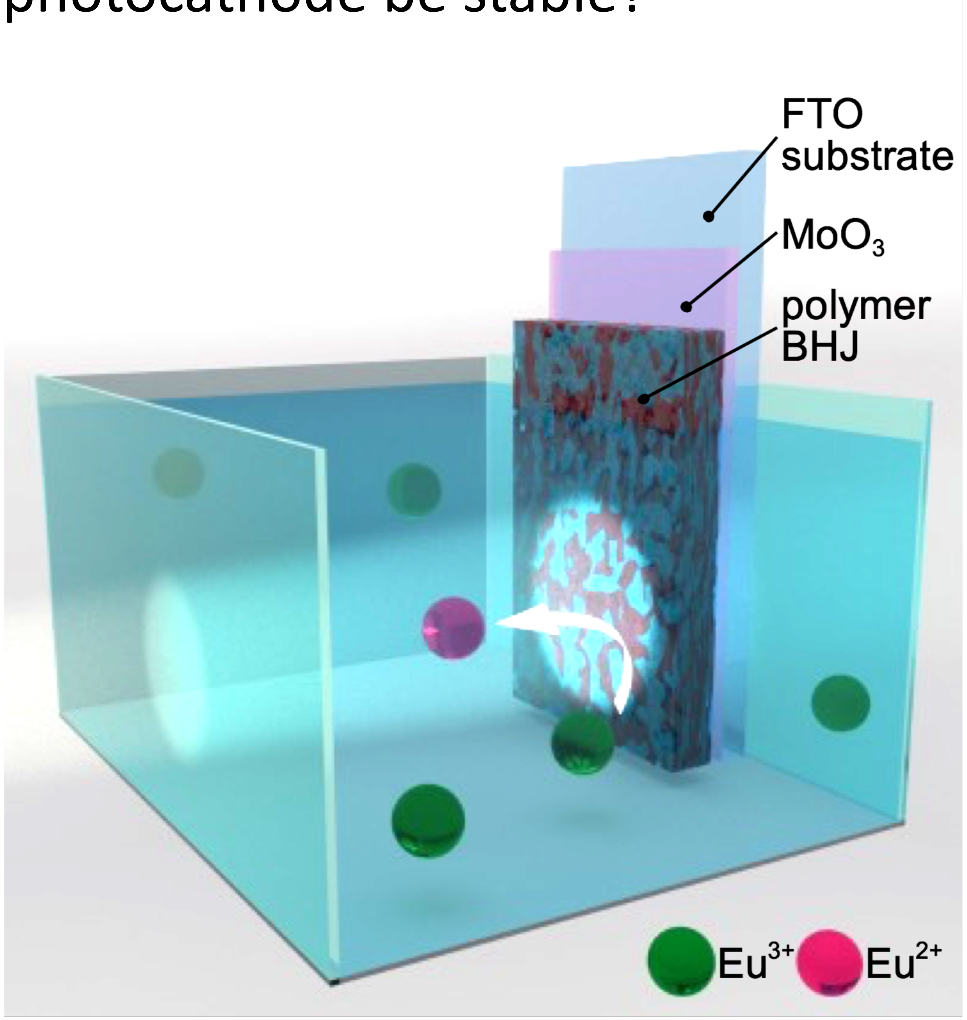
M. Haro et al., *J. Phys. Chem. C* **2015**, *119*, 6488.

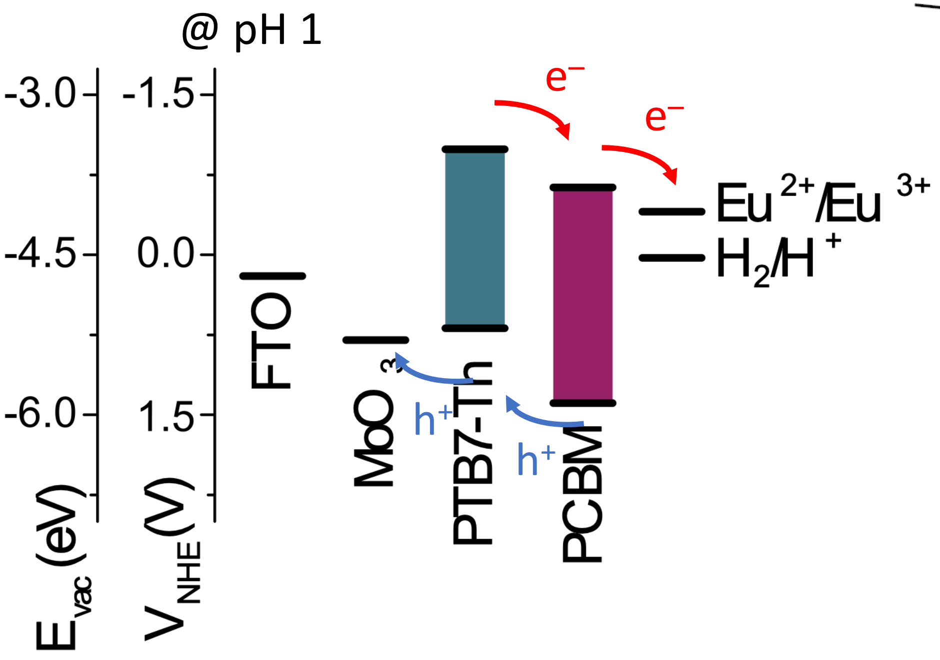


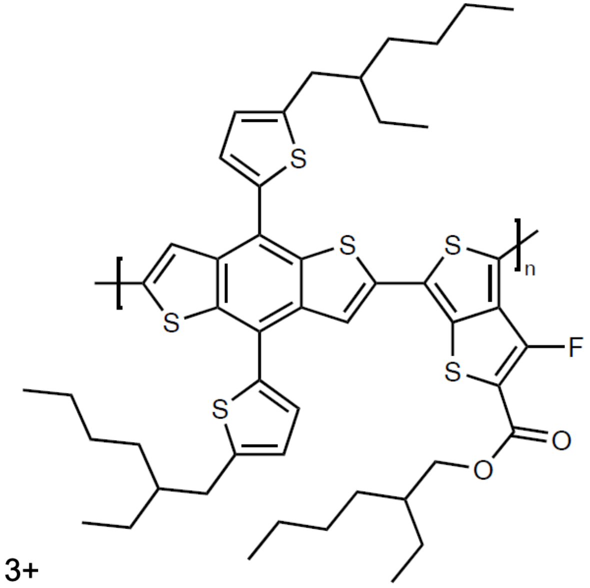
H. Comas Rojas et al., *Energy & Environmental Science* **2016**, *9*, 3710.

Why is a BHJ in Water So Unstable?

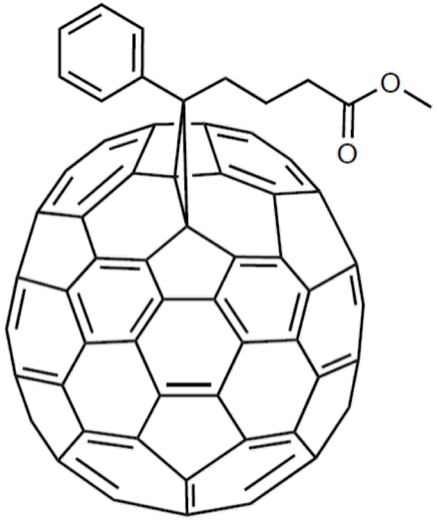
Or can a direct BHJ/water junction photocathode be stable?







PTB7-Th



$PC_{70}BM$

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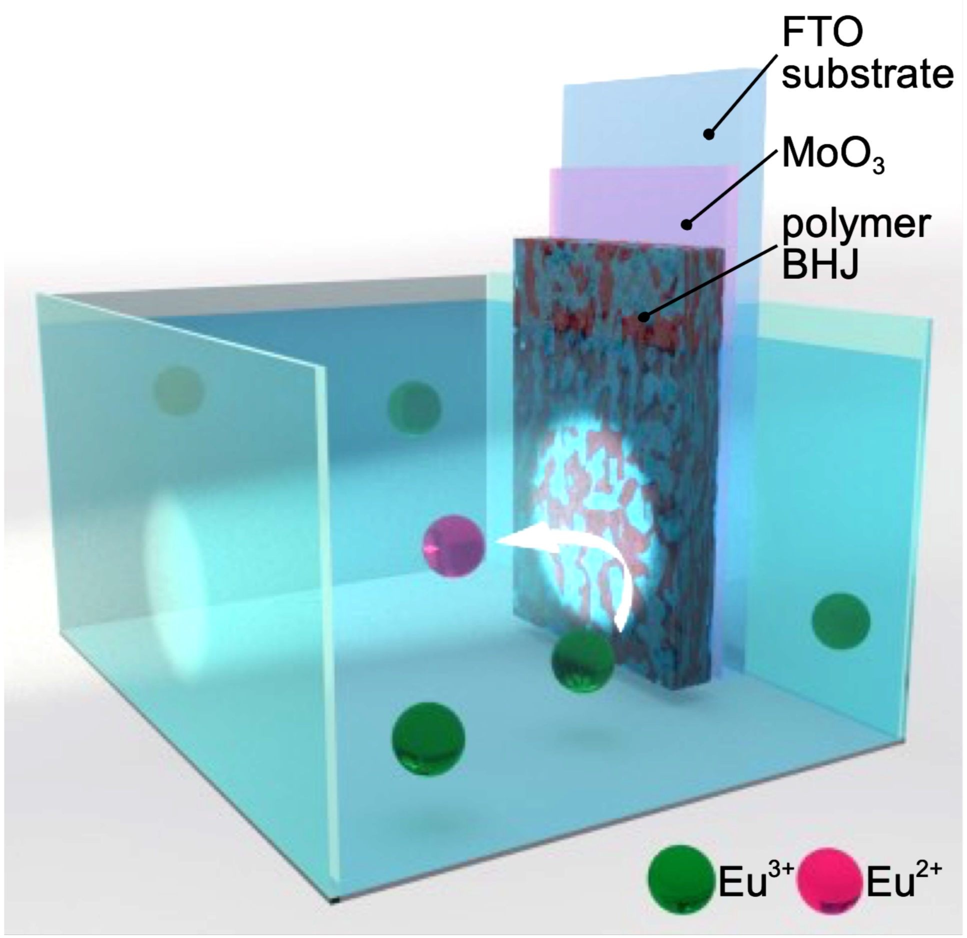

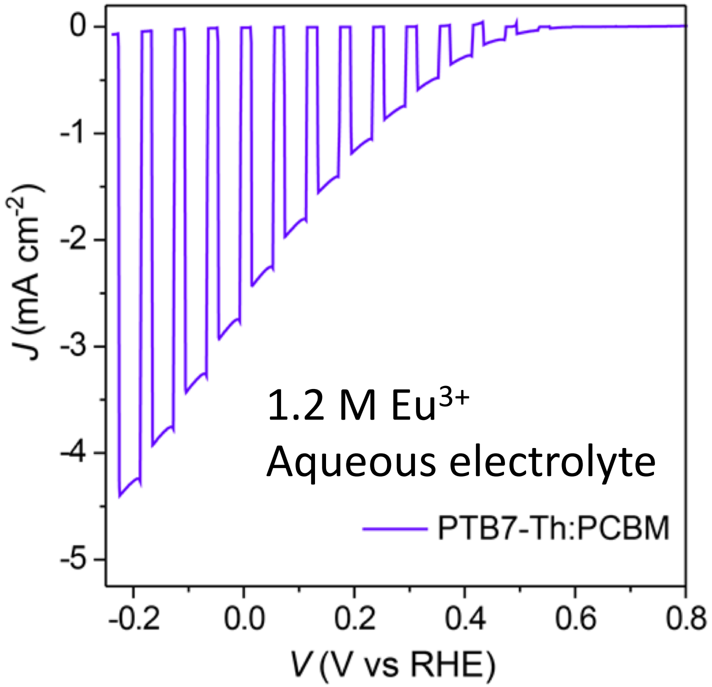

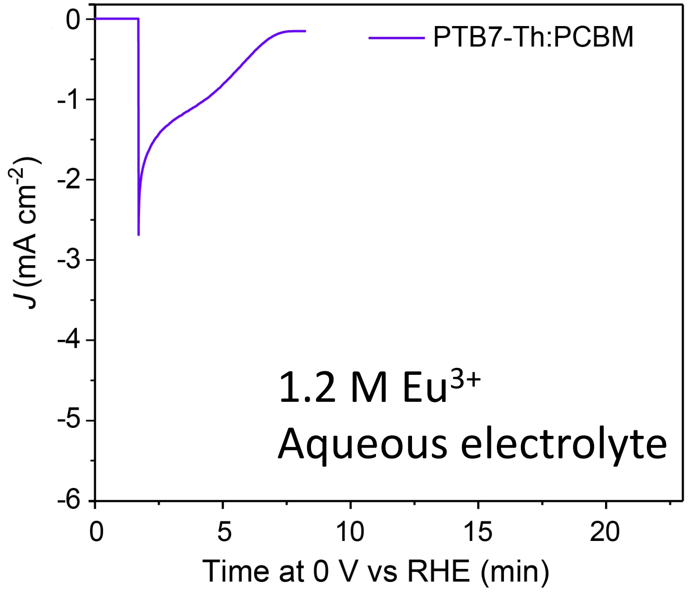

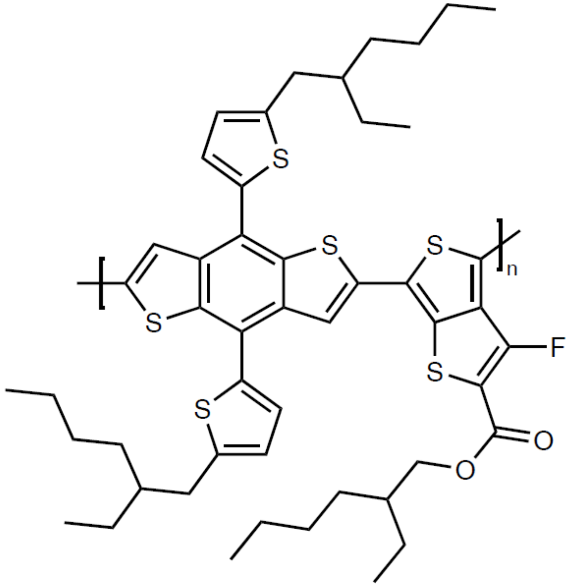

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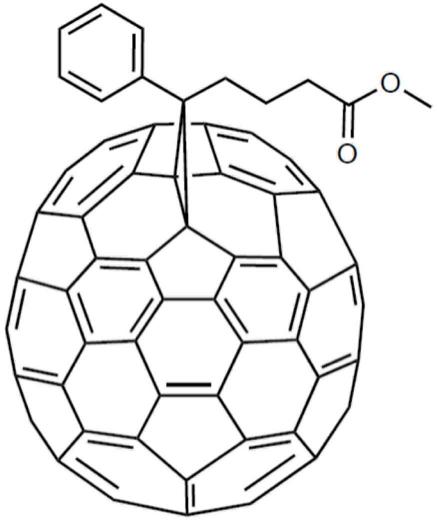

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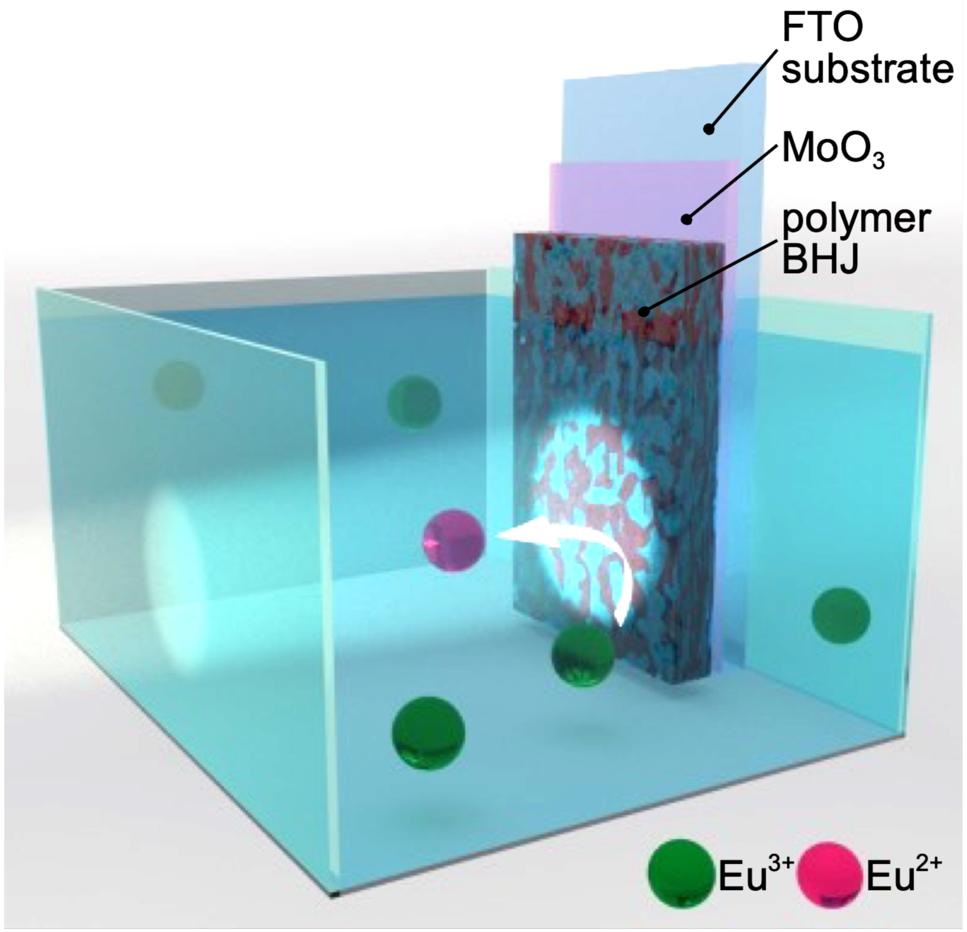

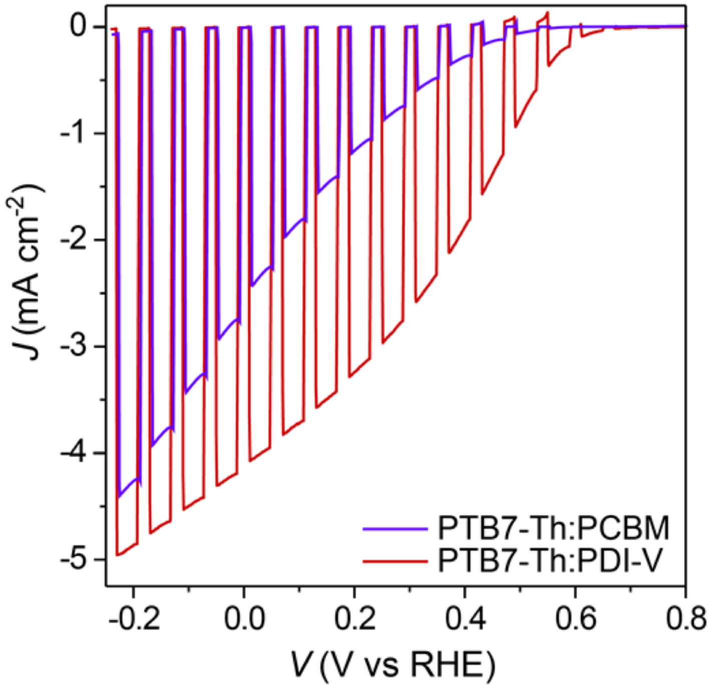

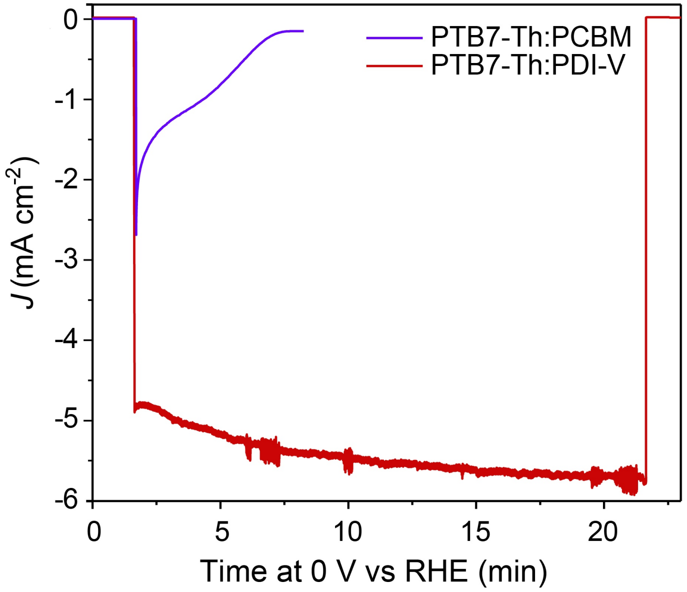

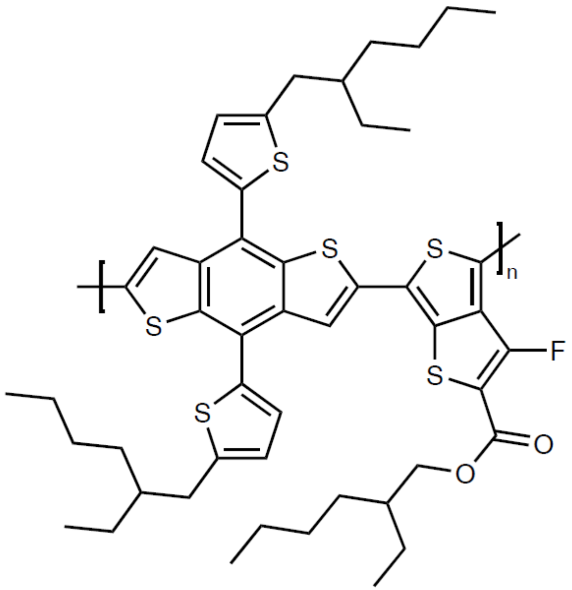

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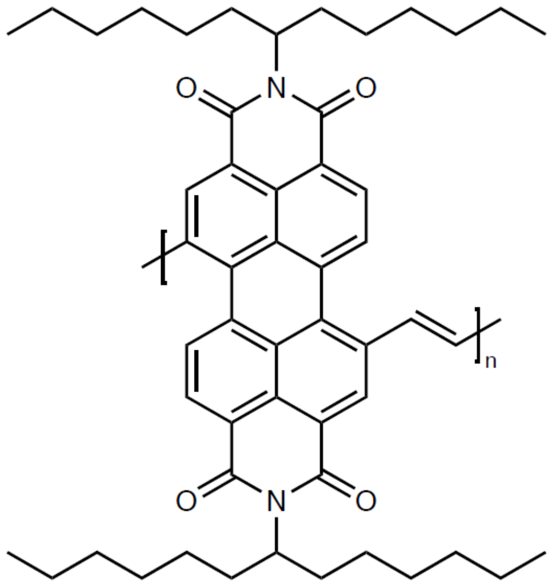
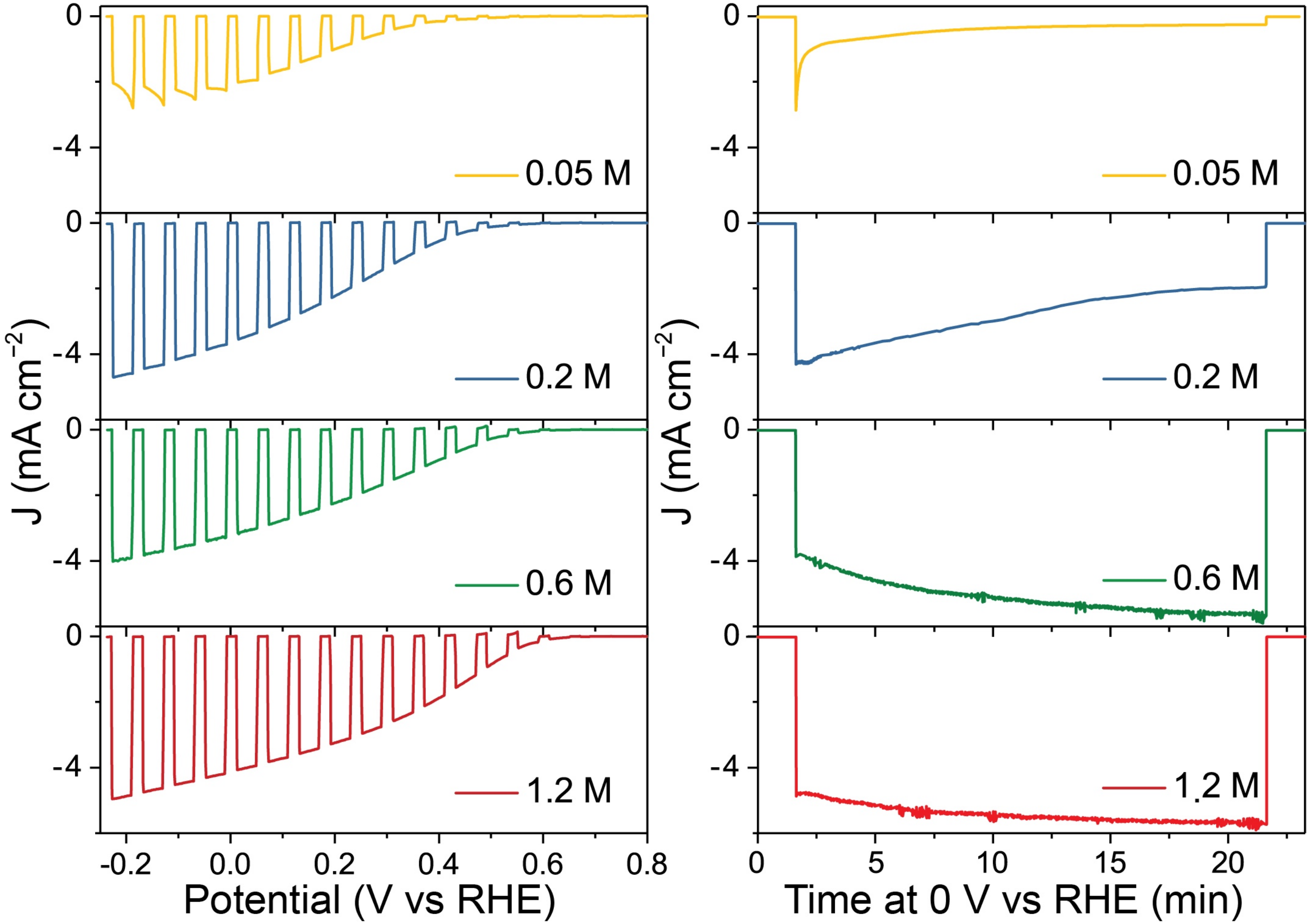


PDI-V

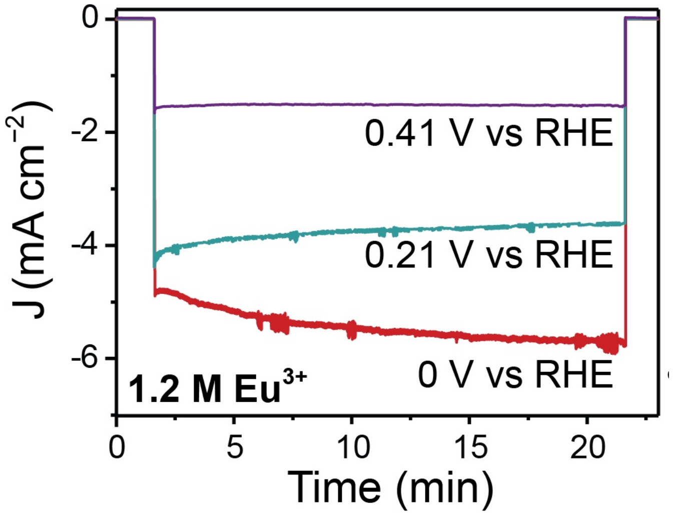
- Jun-Ho YUM, junho.yum@epfl.ch

Insight into Stability of NFA BHJ with Electron Scavenger

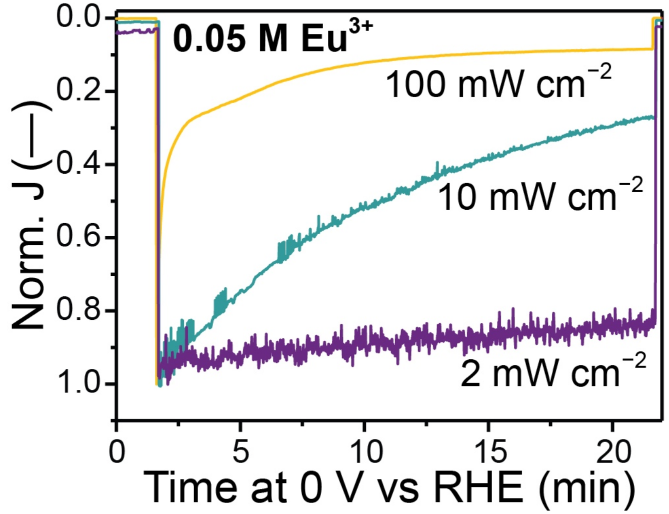
Changing the Eu^{3+} concentration:



Changing the applied potential:



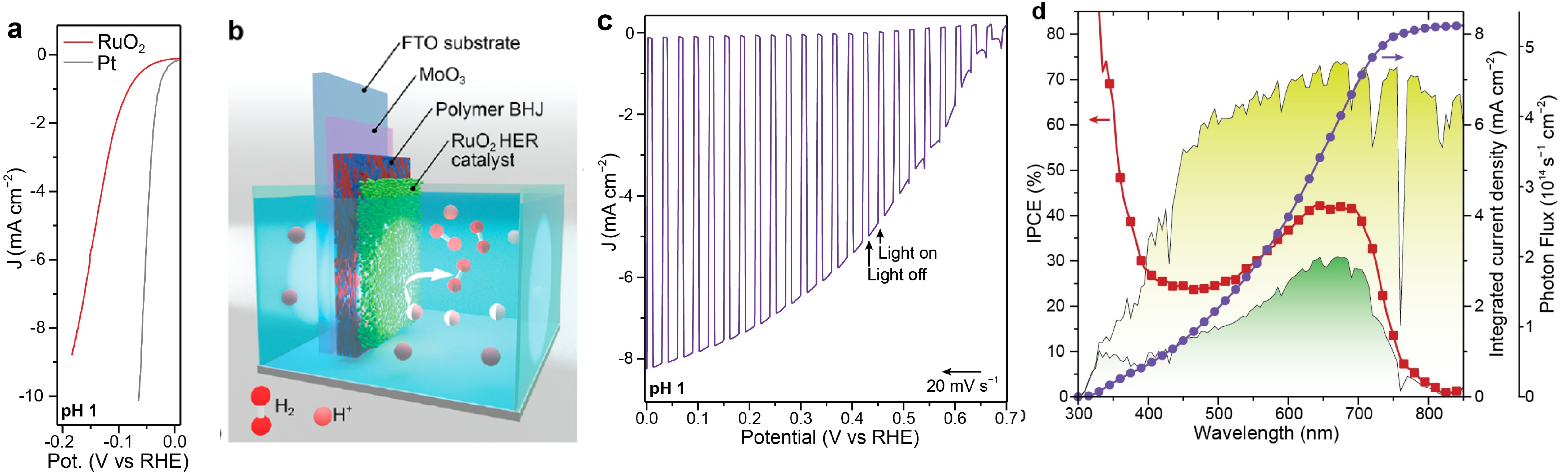
Changing the illumination intensity:



L. Yao et al. *J. Am. Chem. Soc.*, **2020**, 142, 17, 7795–7802

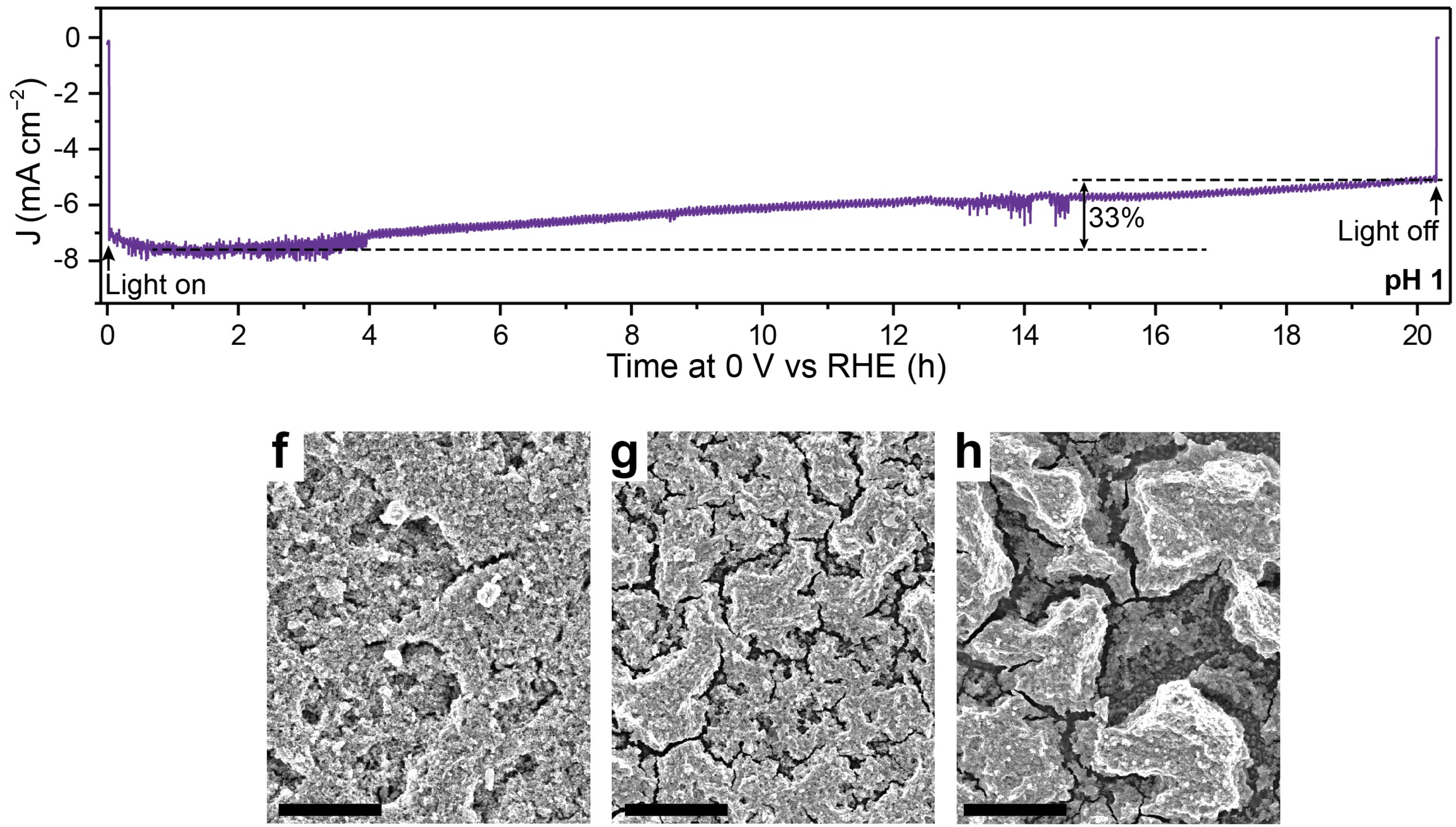
Adding a Catalyst to Drive H_2 Production

"Dark" electro-
catalysis (on FTO)



L. Yao et al. *J. Am. Chem. Soc.*, **2020**, 142, 17, 7795–7802

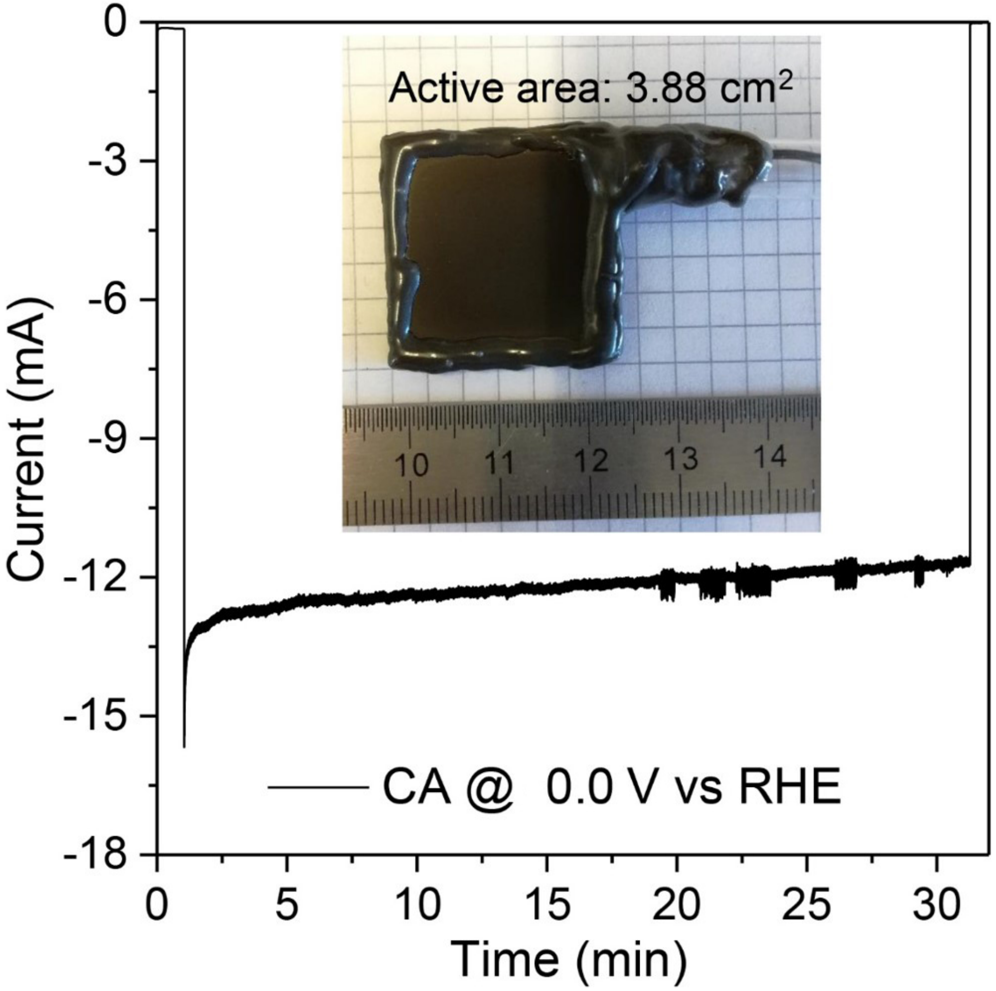
Stability with Catalyst



Scale bar: 1 µm

L. Yao et al. *J. Am. Chem. Soc.,* **2020**, 142, 17, 7795–7802

Large Area Demonstration



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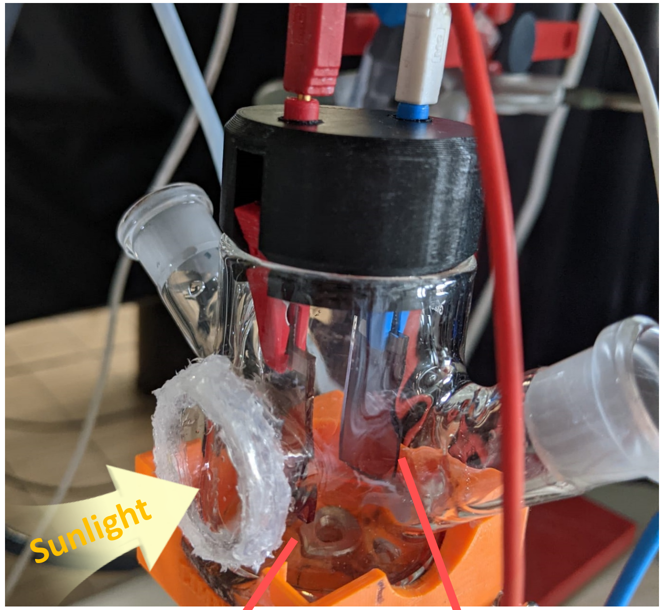
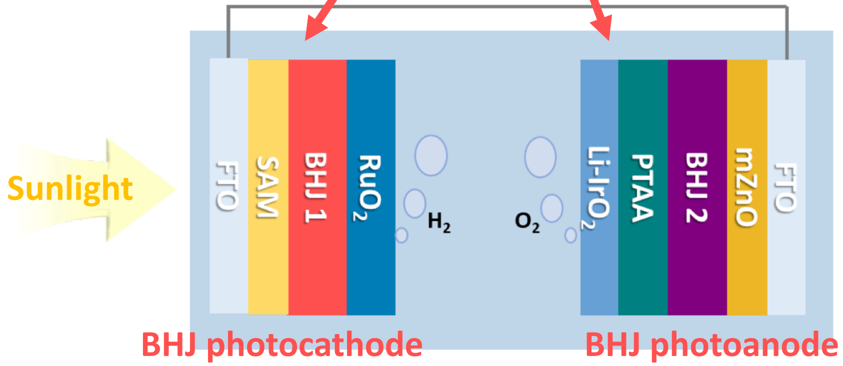
What is Next?

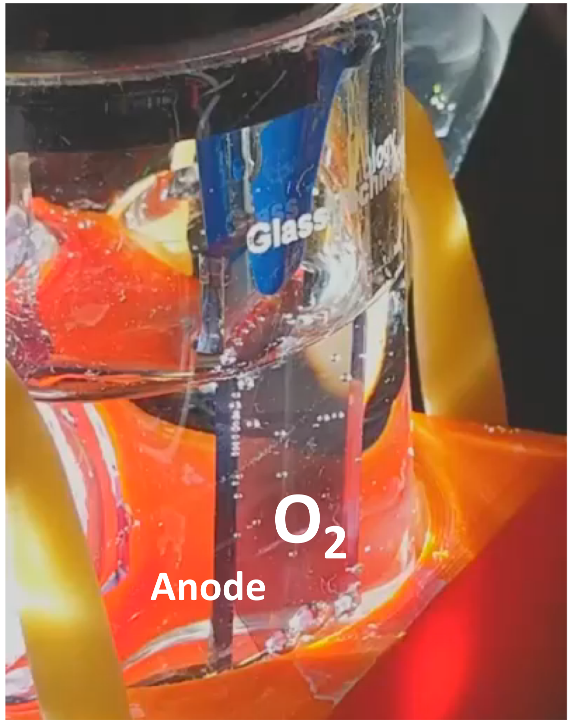




Complete solar water splitting at zero-bias
Without any capsulation or passivation

[Back]

[Side]



D. Zhang, et al., Adv. Energy Mater., **2022**, 2202363.