THE UNIVERSITY OF MELBOURNE

Melbourne Energy Institute

Artificial Leaf for Hydrogen Production

Presenter: **Joshua Butson**, *University of Melbourne*

Outline

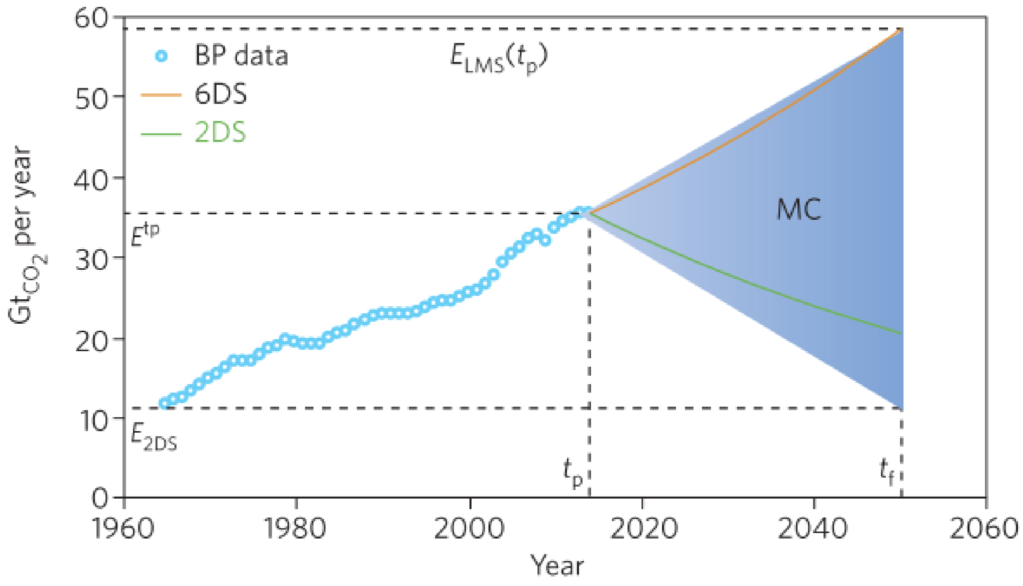
1. Solar Water Splitting
2. Cocatalyst Foils
3. GaAs Artificial Leaf
4. Triple-Junction Device
5. Conclusion and Outlook
6. Acknowledgements

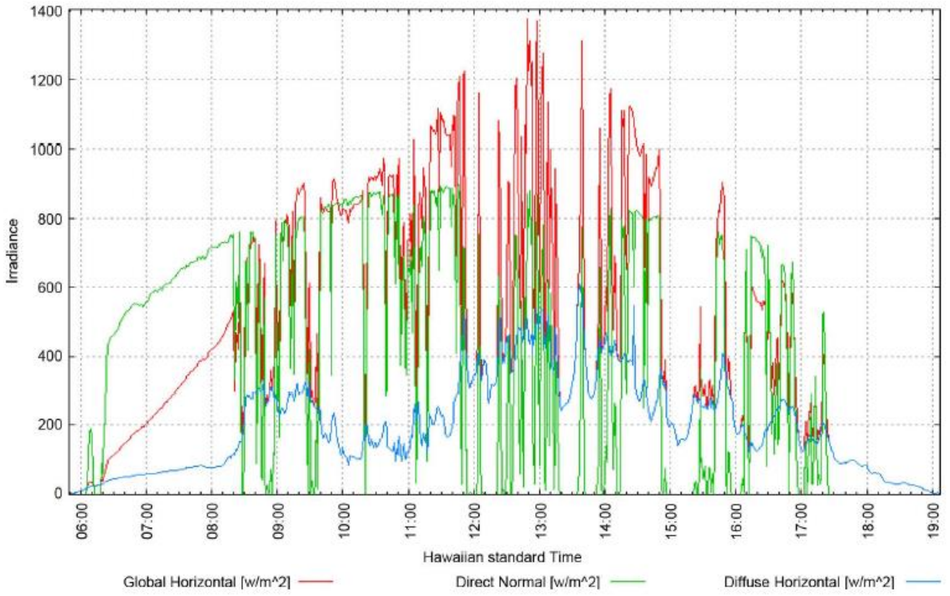
Solar Water Splitting

Solar Water Splitting

Benefits and challenges of renewables:

- Fossil fuels, CO_2 emissions, climate change.
- Renewables, readily available, cost-competitive.
- Intermittency a challenge, storage methods needed.



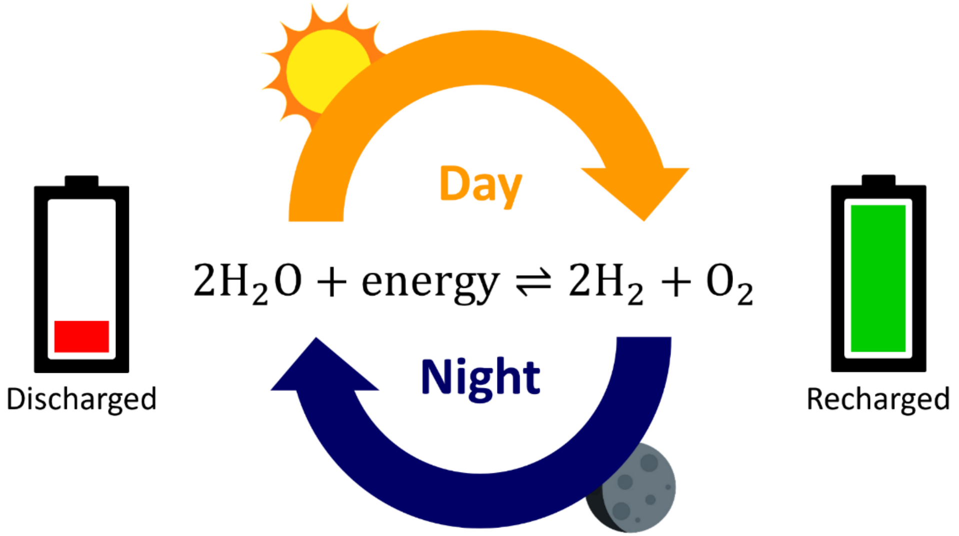


Nat. Clim. Chang. 2017, **7**, 243; *IEEE Trans. Smart Grid* 2012, **3**, 850.

Solar Water Splitting

Molecular hydrogen H_2:

- Very energy-dense chemical fuel (2.7× gasoline).
- Grey hydrogen, 3% of global CO_2 emissions.
- Green hydrogen economy has been proposed.



Renew. Sustain. Energy Rev. 2015, **51**, 623; *Science* 2019, **364**, eaav3506; *Energy Environ. Sci.* 2021, **14**, 1517.

Solar Water Splitting

Water electrolysis:

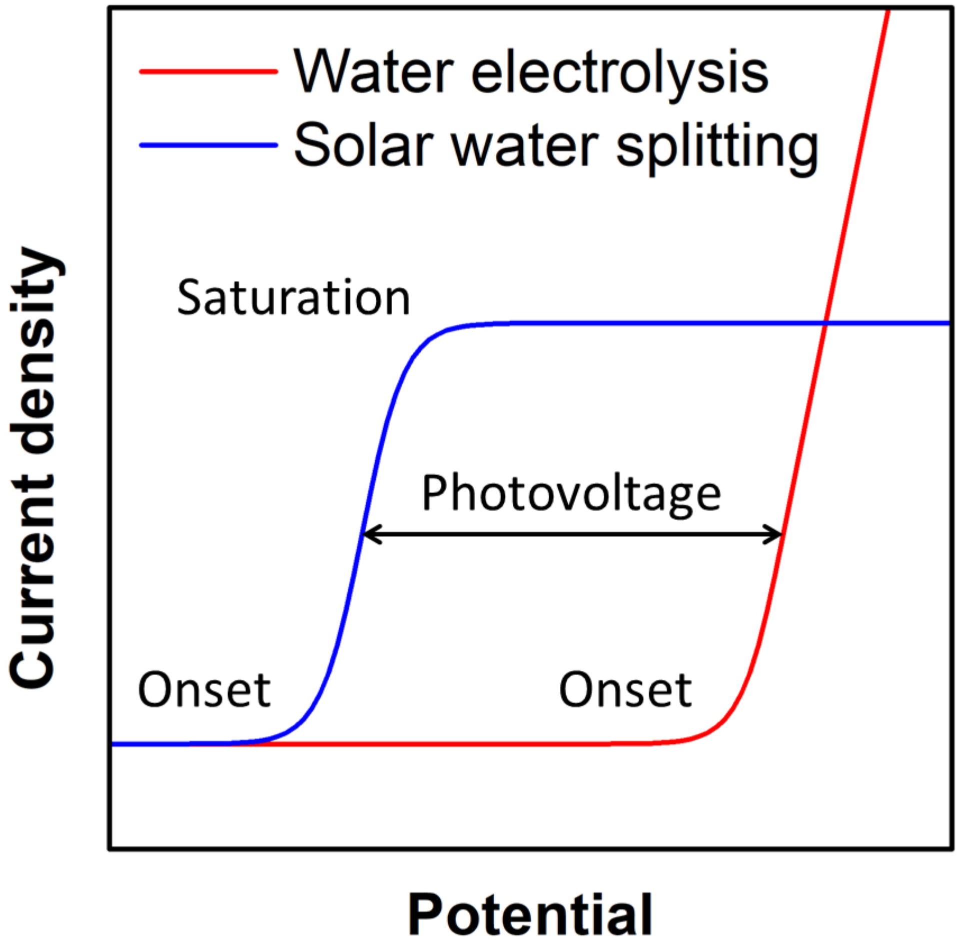
- OER at the anode.

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

- HER at the cathode.

$$2H^+ + 2e^- \rightarrow H_2$$

- Cell potential 1.23 V.
- +100 mV for the HER.
- +300 mV for the OER.



Solar Water Splitting

Challenges:

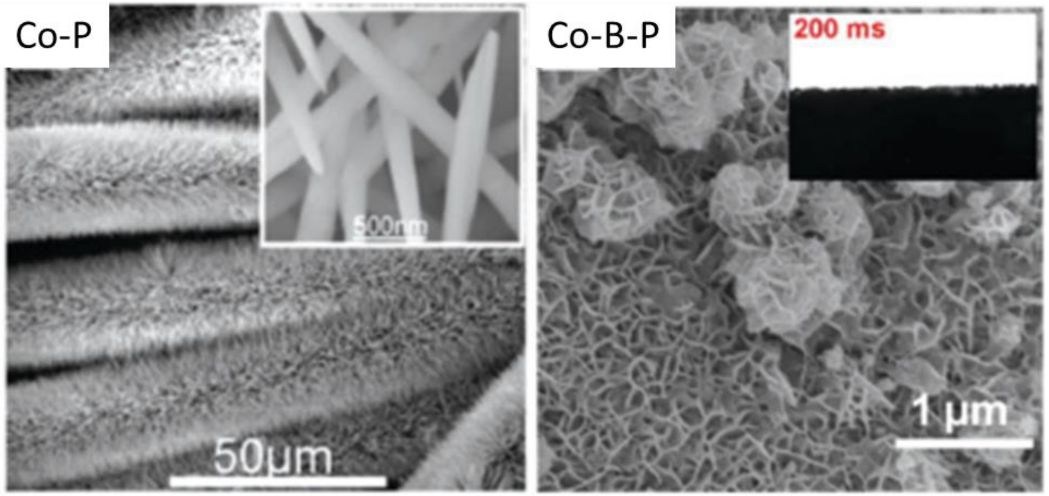
- Efficiency, stability, cost.
- Concentrated illumination can reduce material costs and improve energetics.
- Thermal management critical.
- Immersed devices, electrolyte can double as coolant.
- Transport heat from photoabsorbers to electrodes.
- All components maintain suitable temperatures.

Cocatalyst Foils

Cocatalyst Foils

Earth-abundant cocatalysts:

- Transition metals and compounds.
- Often nanostructured and therefore opaque.
- Deposited via solution-based methods.
- Difficult to combine with semiconductors.

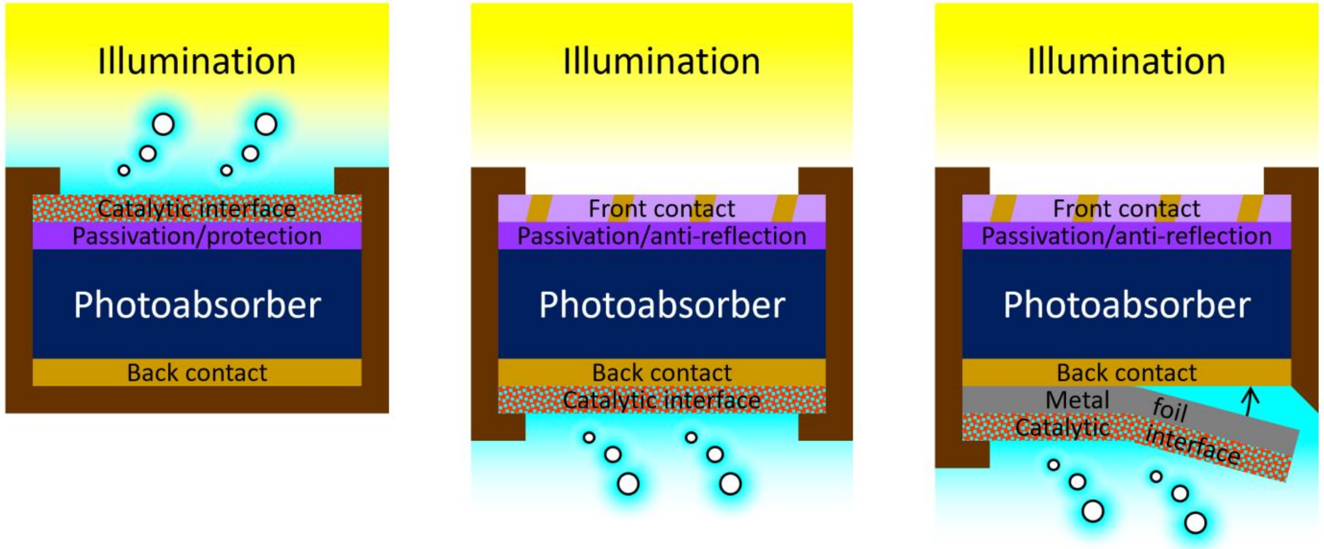


Chem. Soc. Rev. 2014, **43**, 7787; *Nat. Rev. Chem.* 2017, **1**, 0003; *Adv. Mater.* 2020, **32**, 1806326.

Cocatalyst Foils

Fully decoupled photoelectrodes:

- Light absorption and catalysis are spatially decoupled during device operation.
- Cocatalyst deposition is decoupled from device fabrication



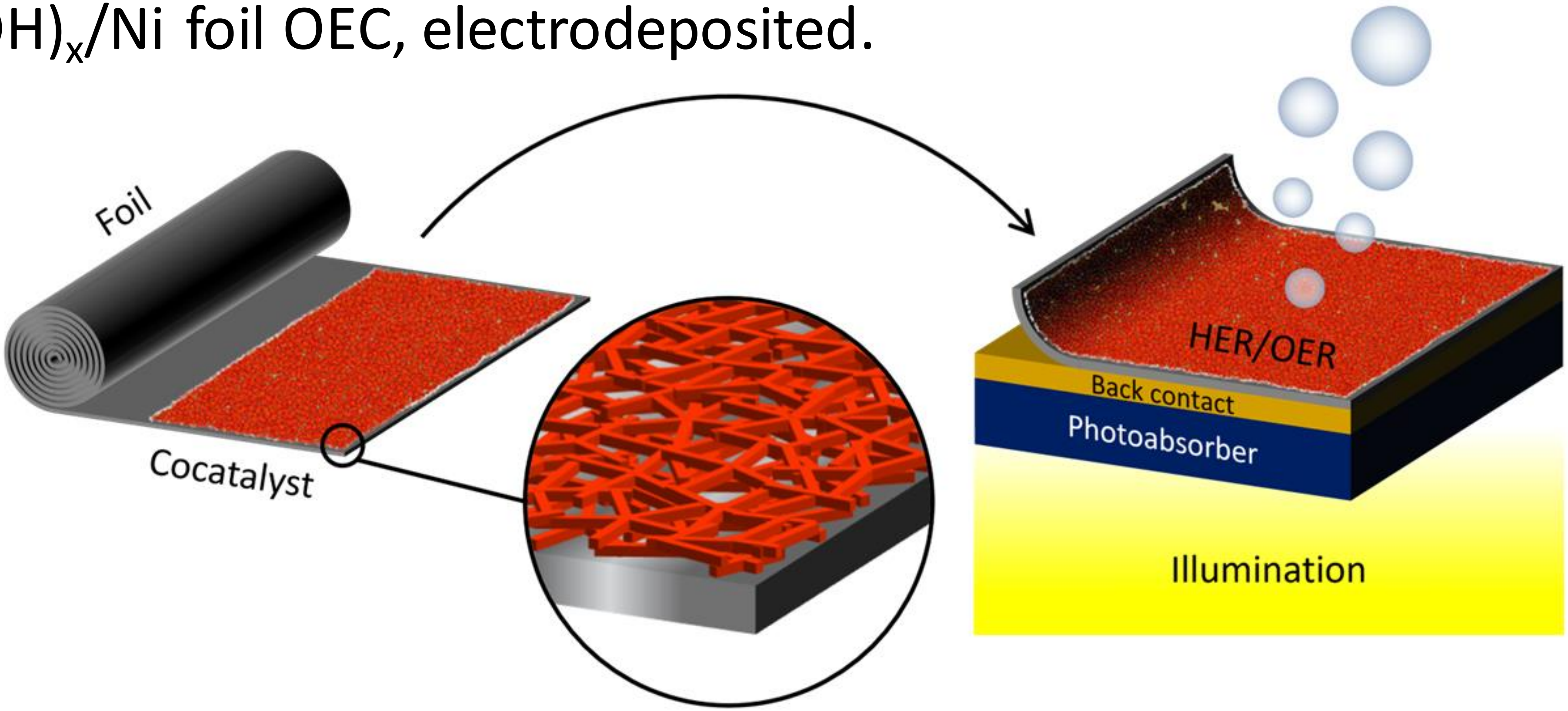
Conventional — Spatially decoupled — Fully decoupled

Adv. Energy Mater. 2022, **12**, 2102752.

Cocatalyst Foils

Earth-abundant cocatalyst foils:

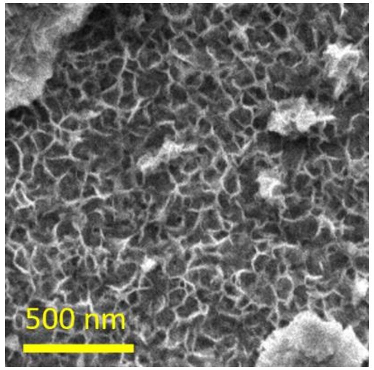
- $NiMo_x$/Ni foil HEC, deposited hydrothermally.
- $NiFe(OH)_x$/Ni foil OEC, electrodeposited.

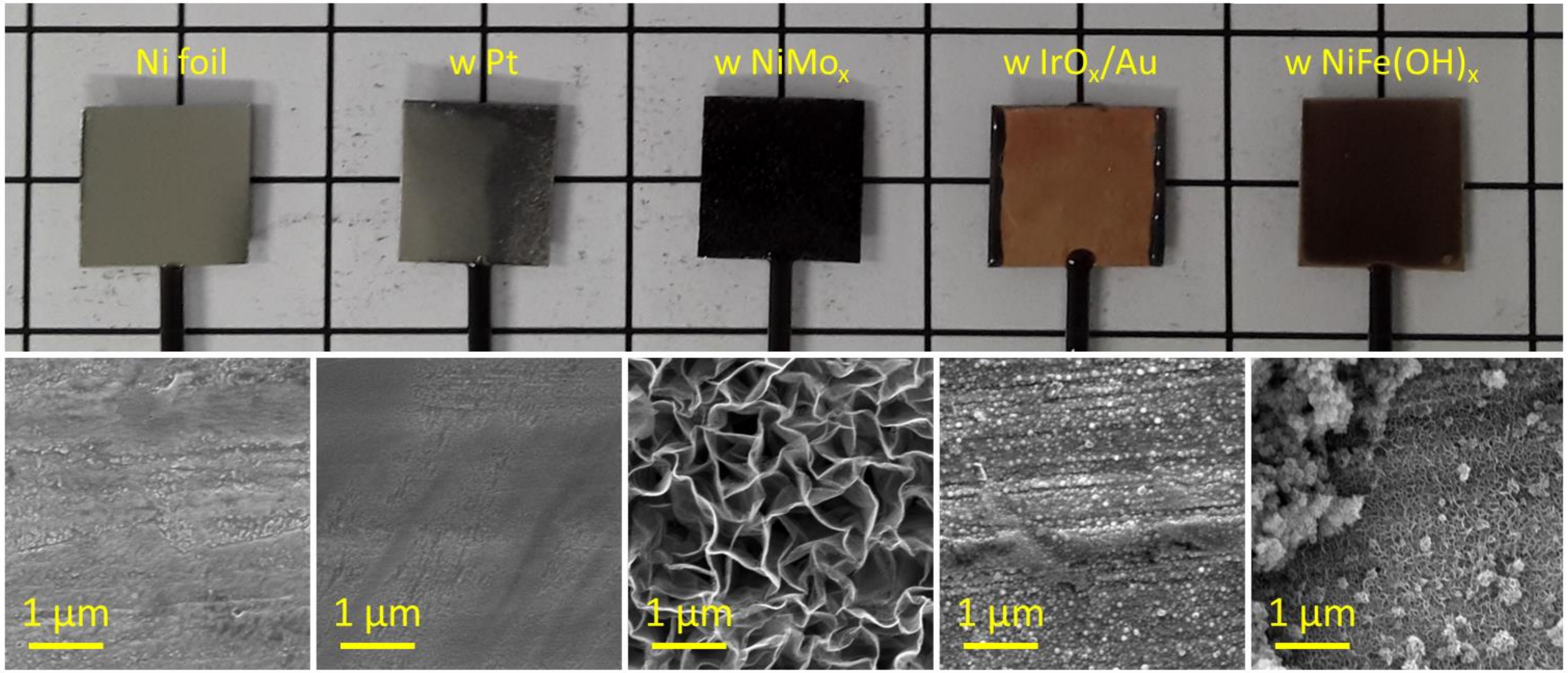


Cocatalyst Foils

Earth-abundant cocatalyst foils:

- $NiMo_x$ flakes, $NiFe(OH)_x$ needles.
- Benchmark noble metal cocatalysts.

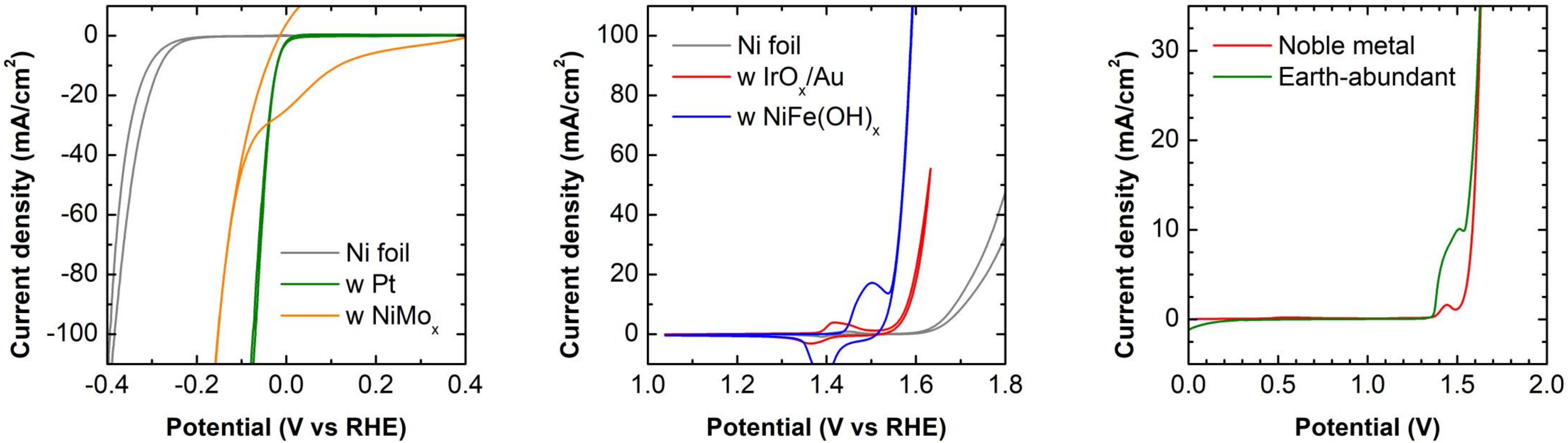




Cocatalyst Foils

J-V characteristics in 1 M NaOH:

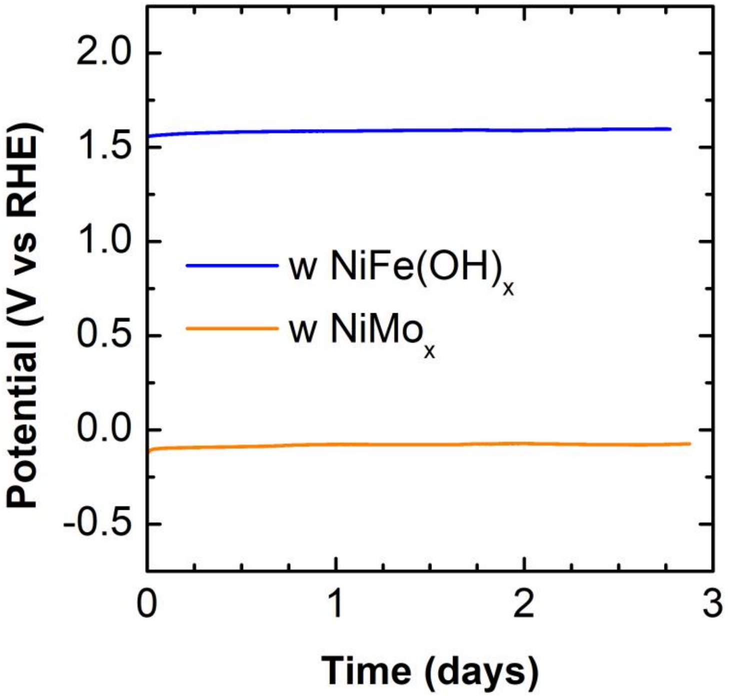
- $NiMo_x$/Ni foil nearly as good as Pt/Ni foil.
- $NiFe(OH)_x$/Ni foil better than IrO_x/Au/Ni foil.
- Collectively, earth-abundant cocatalyst foils as good as noble metals.

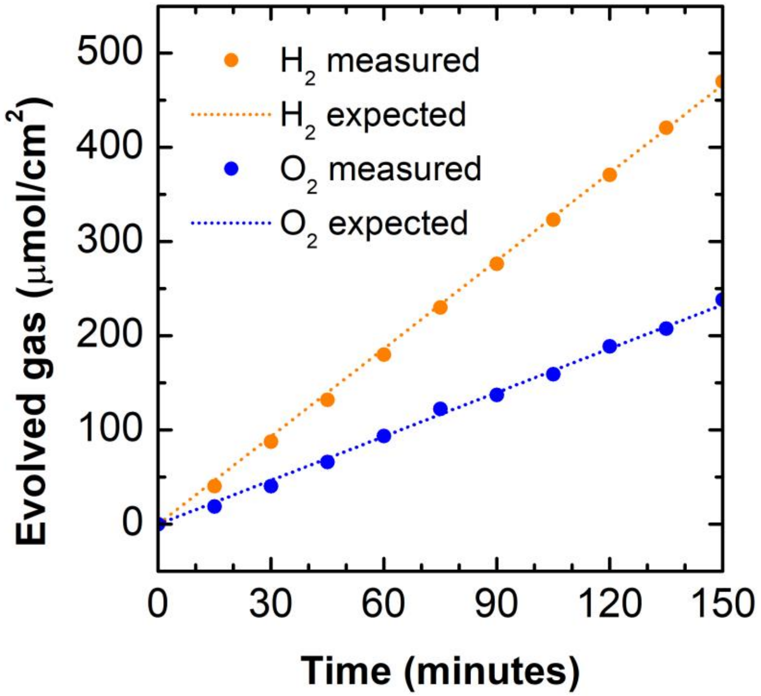


Cocatalyst Foils

Stability in 1 M NaOH:

- Very stable over 3 days.
- Faradaic efficiency very close to 100%.



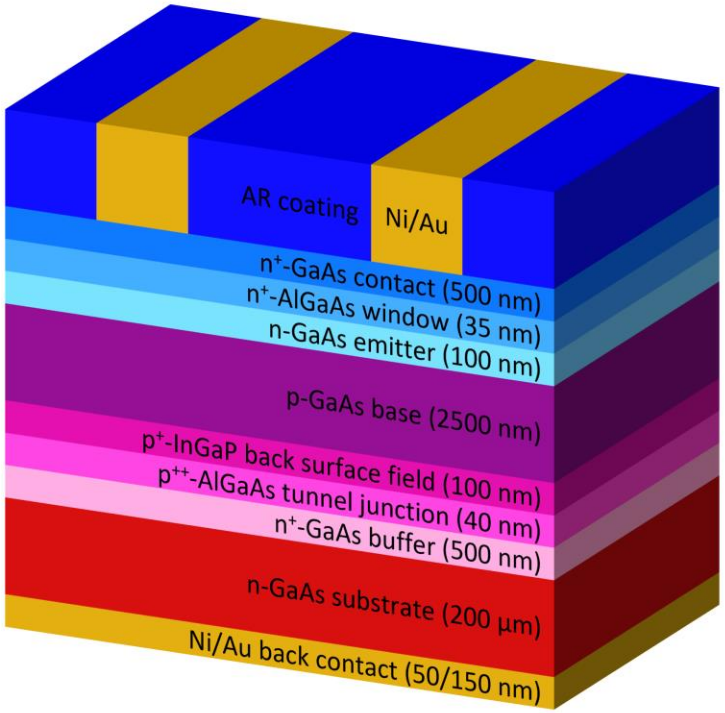


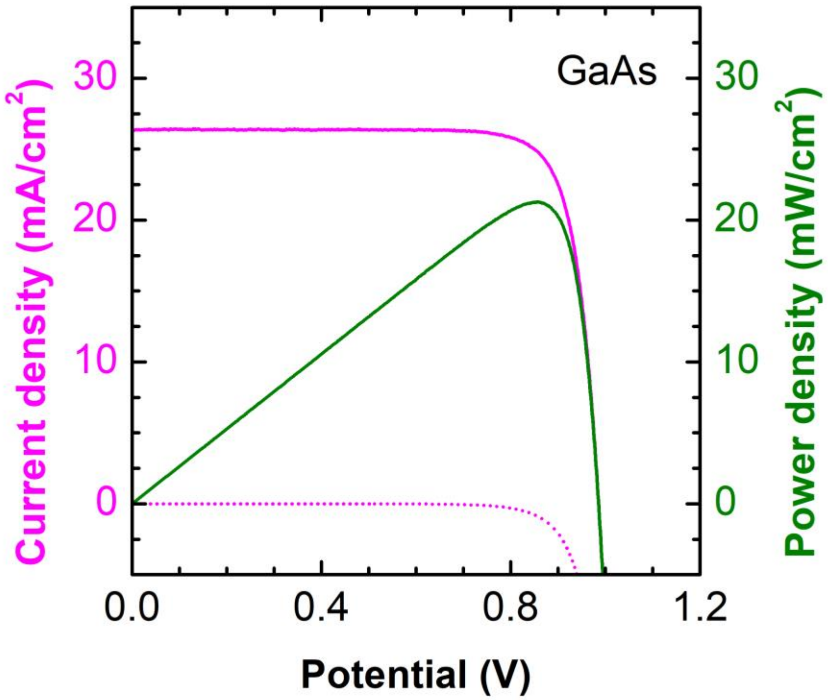
GaAs Artificial Leaf

GaAs Artificial Leaf

GaAs cells:

- Two cells in series required for solar water splitting.
- Direct band gap, can have thin film solar cells, concentrated illumination.

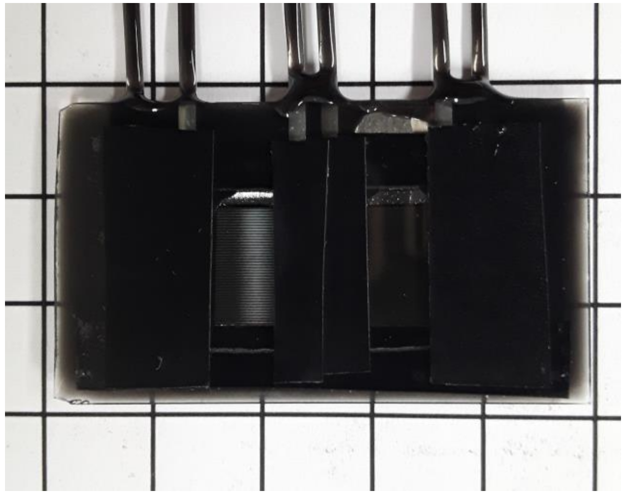


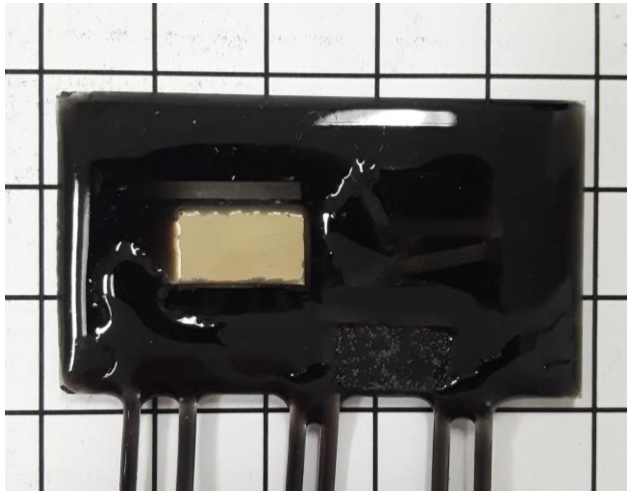


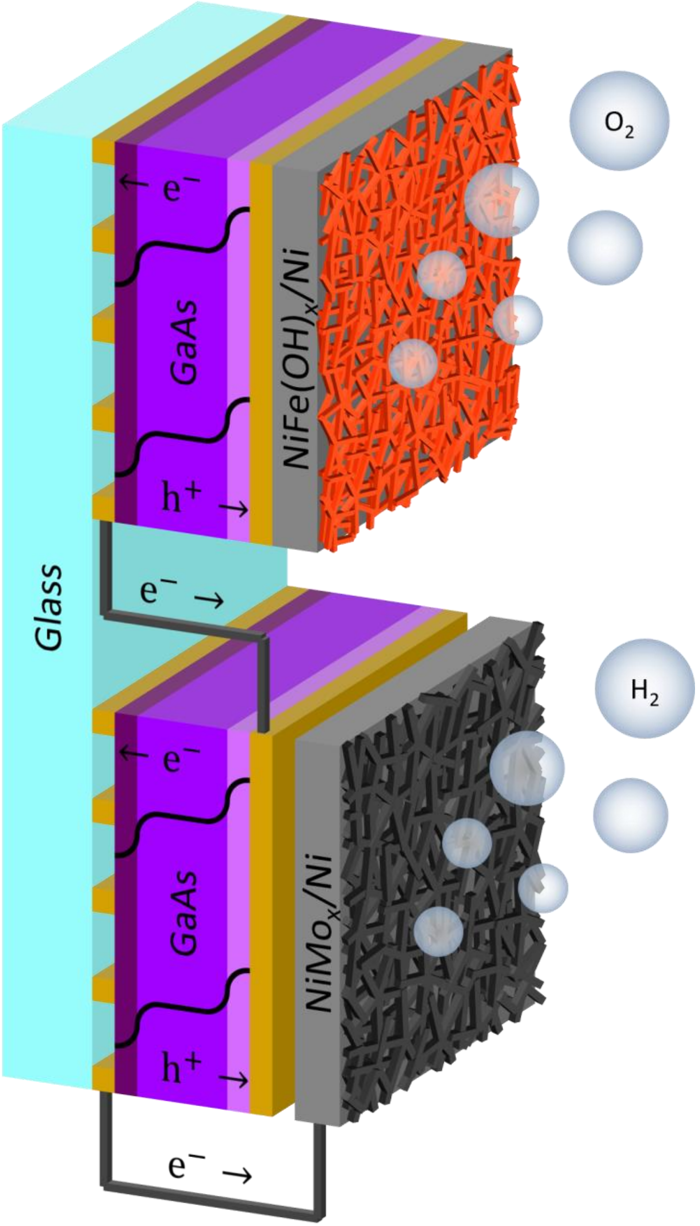
GaAs Artificial Leaf

Construction of artificial leaf:

- Two GaAs cells in series.
- Fully decoupled photoanode.
- Wired photocathode.
- Ag bars, Ag paint, glass, epoxy.





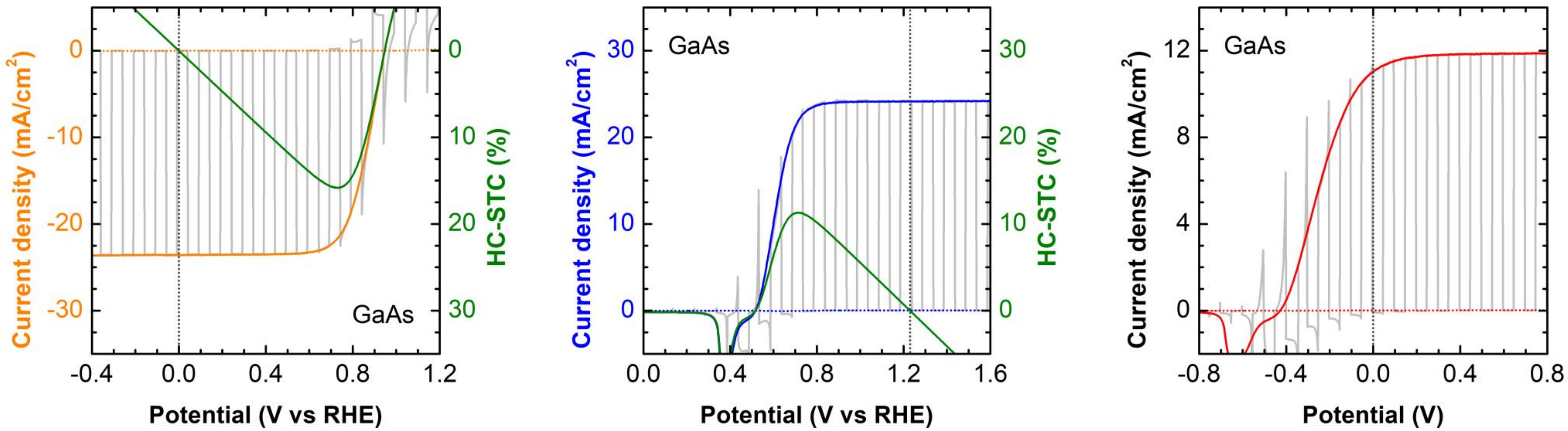


GaAs Artificial Leaf

J-V characteristics in 1 M NaOH:

$$\eta_{\mathrm{STH}} = \frac{1.23\ (\mathrm{V})\ \times\ J\ (\mathrm{mA/cm^2})\ \times\ \eta_{\mathrm{F}}}{P_{\mathrm{in}}\ (\mathrm{mW/cm^2})}$$

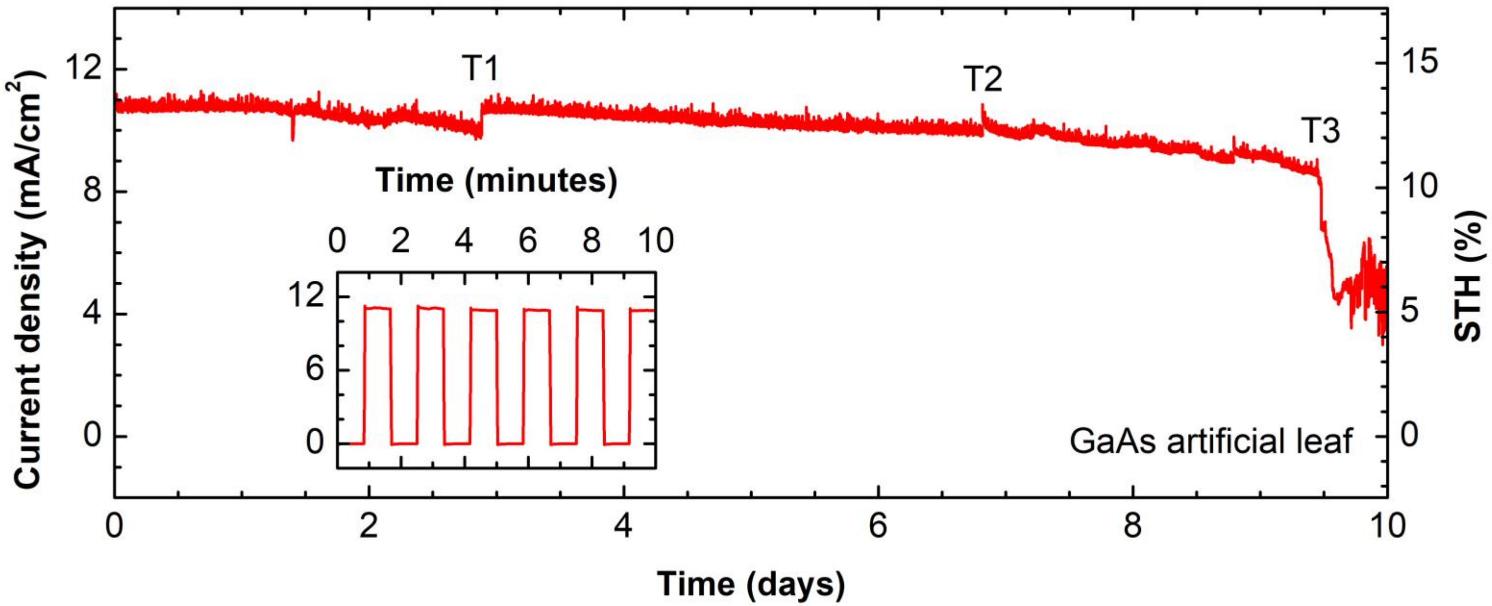
- 11.04 mA/cm^2 at 0 V.
- STH efficiency 13.6%.



GaAs Artificial Leaf

Stability in 1 M NaOH:

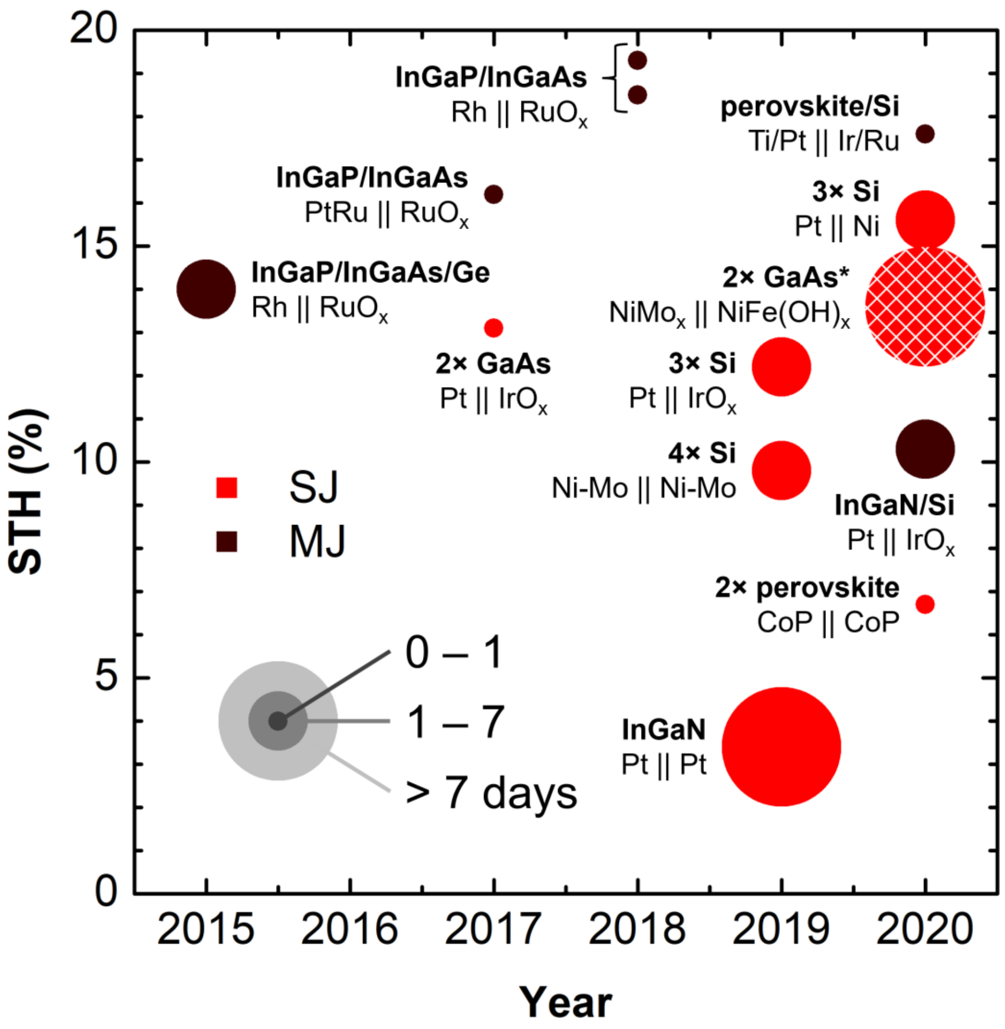
- T1, T2, electrolyte replenished, lamp intensity reset.
- Epoxy delaminated at T2, GaAs cells corroded at T3.
- STH efficiency of over 10% for longer than 9 days.



GaAs Artificial Leaf

Comparison with previously reported devices:

- Systems measured under 1 sun.
- Most efficient with >7 days stability.
- Most efficient with earth-abundant cocatalysts.

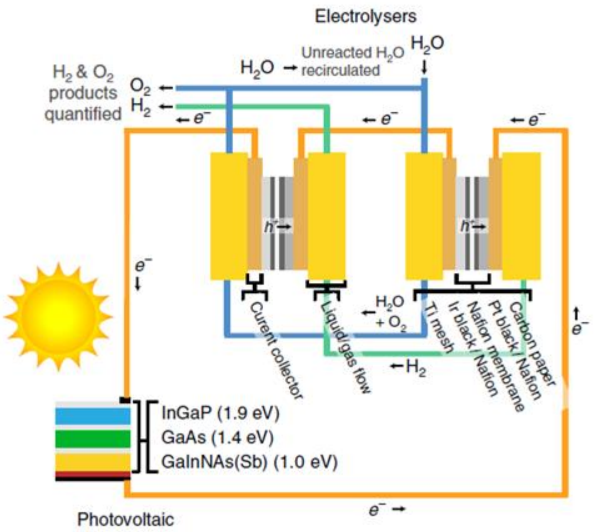


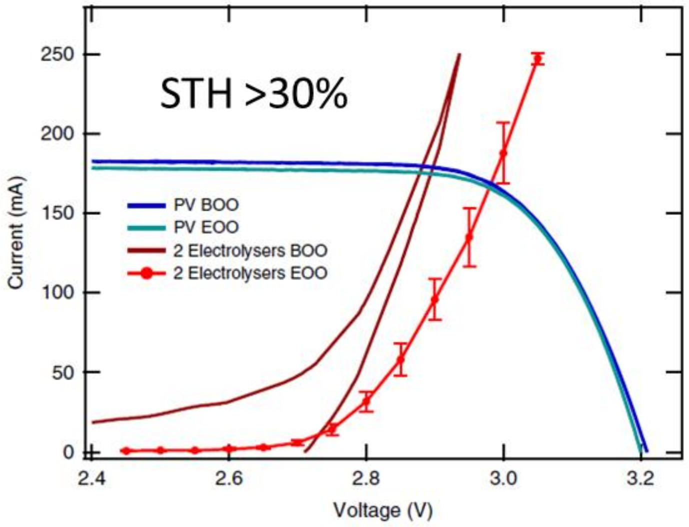
Triple-Junction Device

Triple-Junction Device

Triple-junction cells:

- More subcells, higher PV efficiency.
- Double-junction cells “best” for solar water splitting.
- Triple-junction cells, excess photovoltage.
- Can adjust the ratio of cells to electrolysers.



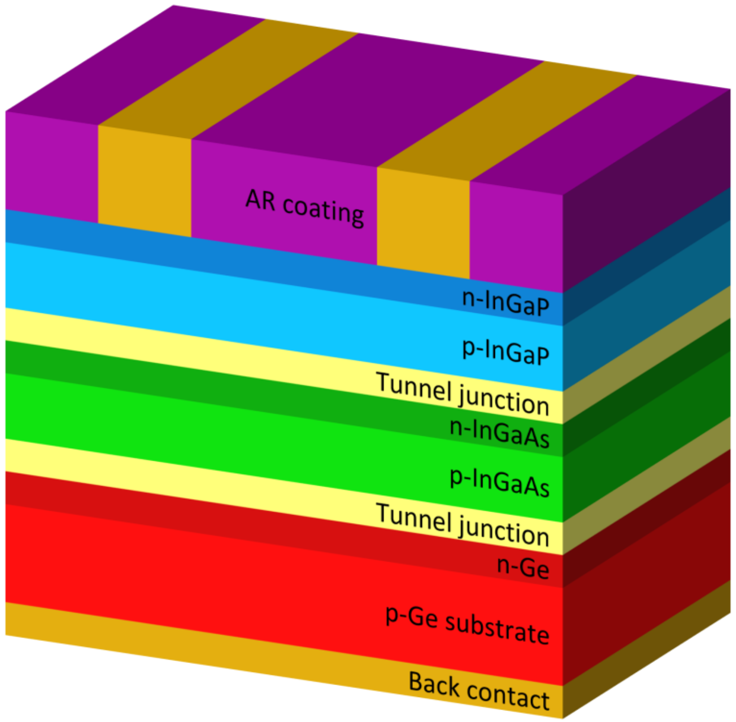


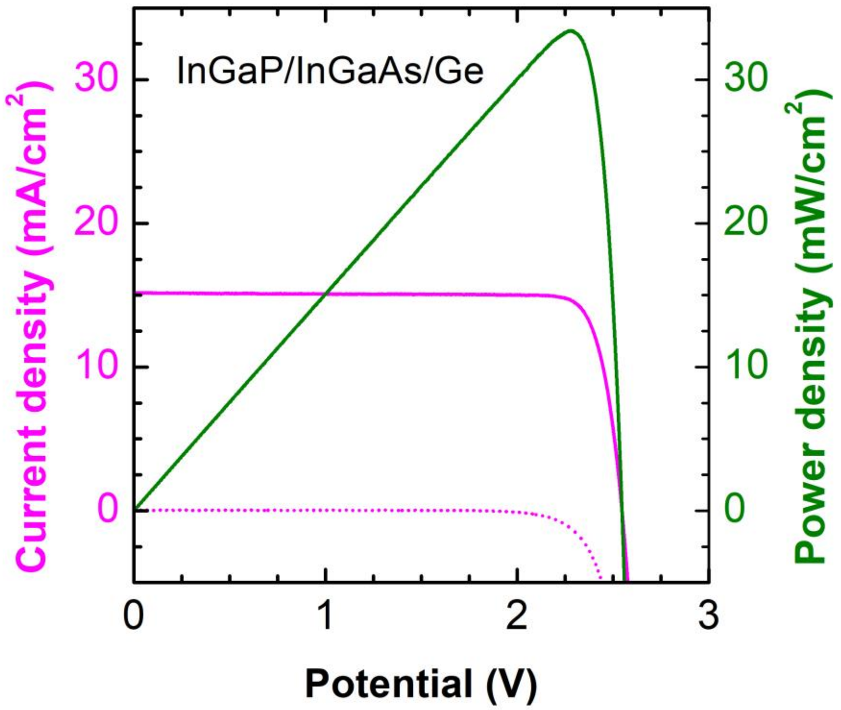
Nat. Commun. 2016, **7**, 13237; *Appl. Phys. Express* 2015, **8**, 107101.

Triple-Junction Device

Triple-junction cells:

- Supplied by MicroLink Devices.
- InGaP/InGaAs/Ge.

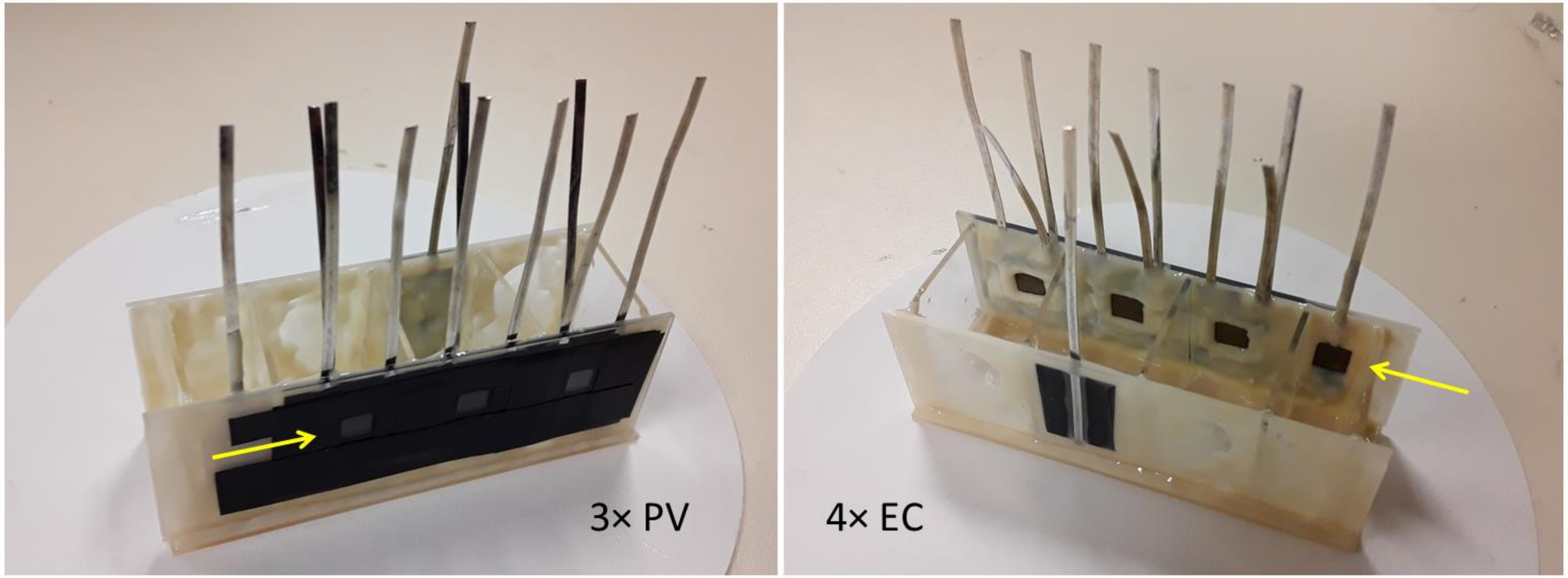




Triple-Junction Device

Construction of triple-junction device:

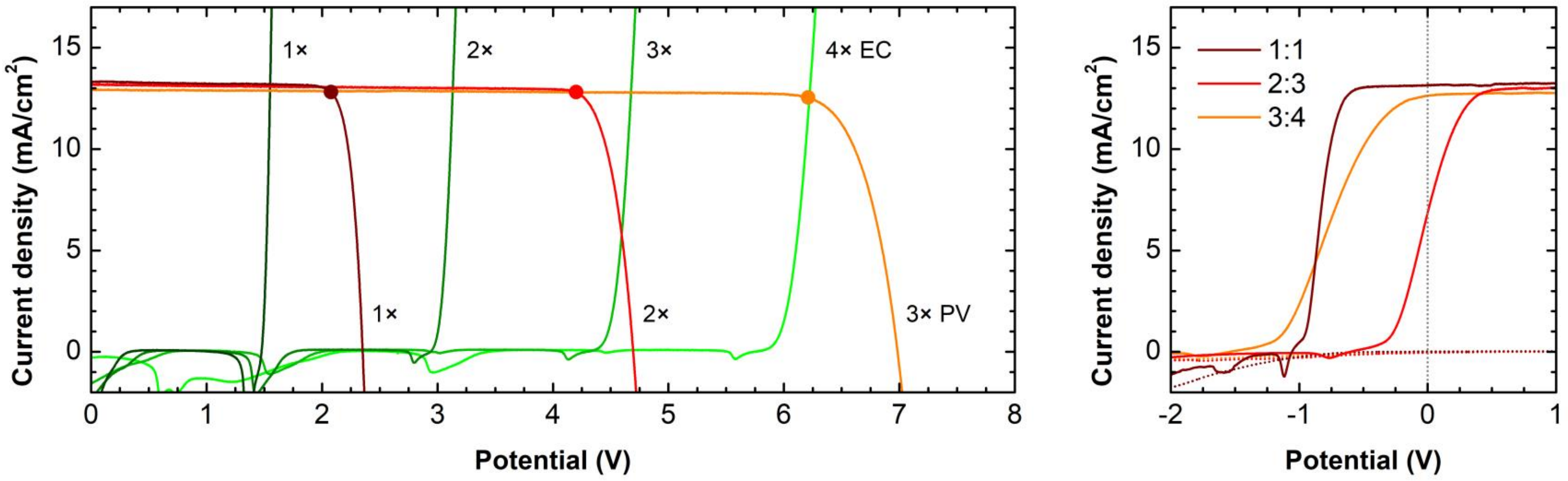
- Fully decoupled photoanodes with $NiFe(OH)_x$/Ni foil.
- $NiMo_x$/Ni foam cathodes (not pictured).
- Three photoanodes, four electrochemical cells.



Triple-Junction Device

J-V characteristics in 1 M NaOH:

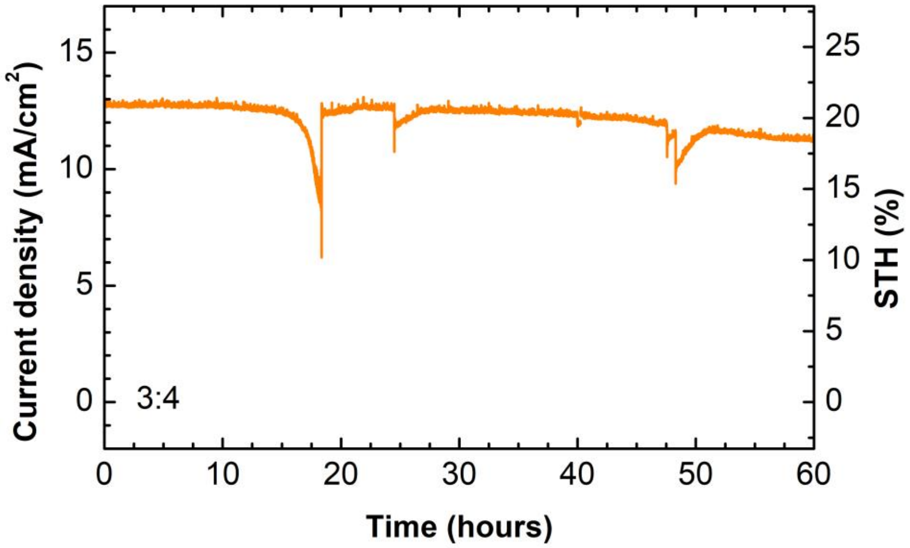
- Each photoanode provides over 2 V.
- Each electrochemical cell requires 1.55 V.
- Components in series add linearly.
- 3 photoanodes, 4 electrochemical cells, STH **20.7%**.

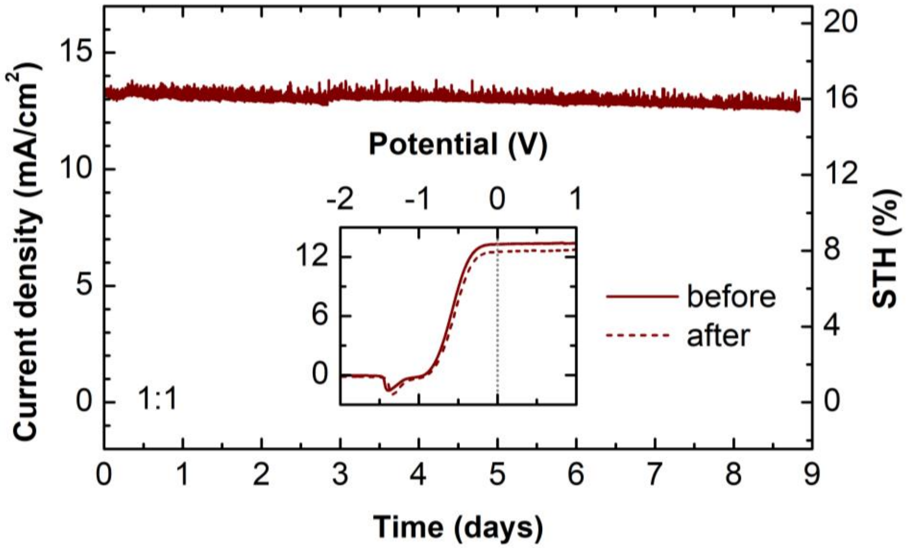


Triple-Junction Device

Stability in 1 M NaOH:

- >20% STH maintained for 40 hours, but epoxy not suitable for long-term stability.
- Single photoanode with better epoxy maintains very stable photocurrent for nearly 9 days.

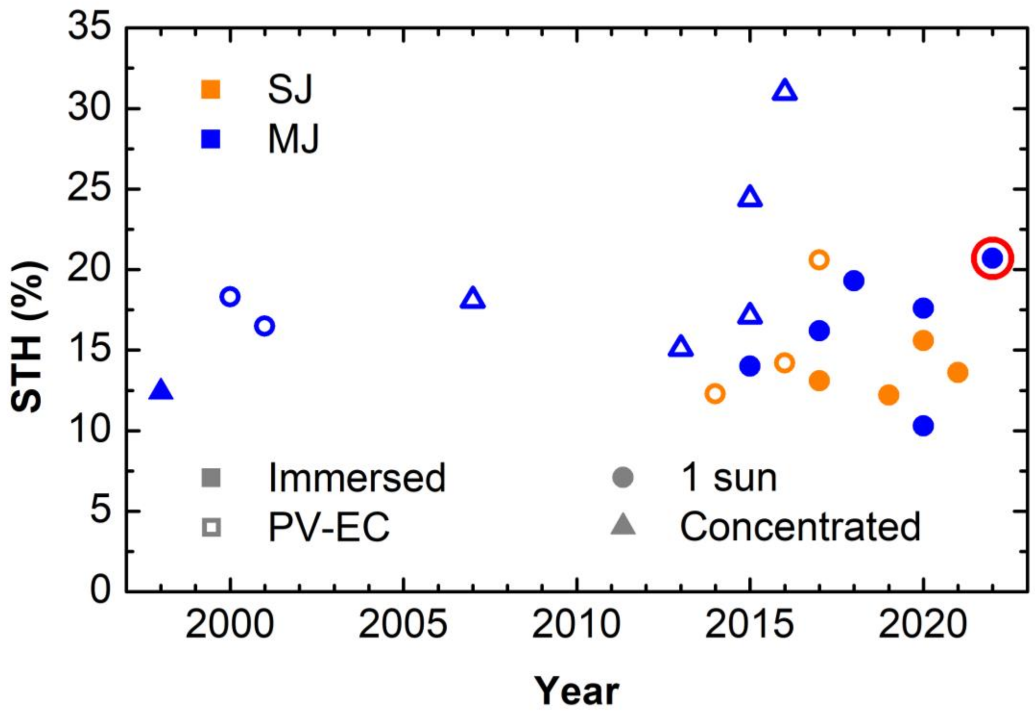




Triple-Junction Device

Comparison with previously reported devices:

- Compares very favourably with other systems, both immersed and PV-EC.
- STH exceeded only by systems operating under concentrated illumination.



Conclusion and Outlook

Conclusion and Outlook

Fully decoupled photoelectrodes:

- Constructed using cocatalyst foils.
- Efficient, stable, earth-abundant.
- Paves the way for immersed devices operating under concentrated illumination.

Acknowledgements

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Engineering

Astha Sharma

Doudou Zhang

Hongjun Chen

External

Bin Gong (UNSW)

David Mitchell (UoW)

Helena Wang (UNSW)

Purushothaman Varadhan (DIFFER)

Mihalis Tsampas (DIFFER)

RSPhys admin

ARC

ARENA

And everyone in EME!

THE UNIVERSITY OF MELBOURNE

Melbourne Energy Institute

www.energy.unimelb.edu.au

CONTACT US

mei-info@unimelb.edu.au

Melbourne Energy Institute
Level 1, Melbourne Connect,
700 Swanston St, Carlton
VIC 3053

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