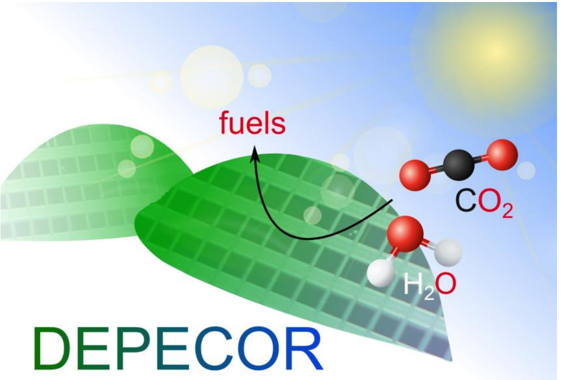
CO_2 as a sustainable source of carbon - Pathways to industrial applications – CO_2-WIN

1st CO_2-WIN conference
8 – 9 June 2021 | virtual event
CO_2WIN
Use Carbon Sustainably

Thomas Hannappel

TU Ilmenau

Fundamentals of Energy Materials



GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Direct efficient photoelectrocatalytic CO_2 reduction

Project partners:

TU Ilmenau
TU München
Helmholtz-Zentrum Berlin
Fraunhofer ISE
AZUR SPACE Solar Power GmbH

TECHNISCHE UNIVERSITÄT ILMENAU
Technische Universität München
HZB Helmholtz Zentrum Berlin
Fraunhofer ISE
AZURSPACE SOLAR POWER GMBH

Assosiated partners:

Joint Center of Artificial Photosynthesis (JCAP)
École Polytechnique Fédérale de Lausanne (EPFL)
Evonik
BASF

JCAP JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE
EVONIK Leading Beyond Chemistry
BASF We create chemistry

CO_2WIN Use Carbon Sustainably
DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.
The SPIRIT of science
TECHNISCHE UNIVERSITÄT ILMENAU

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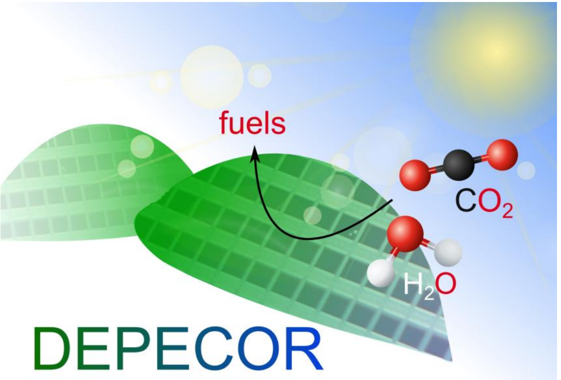

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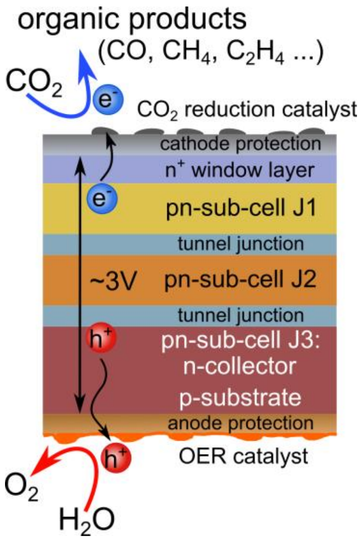
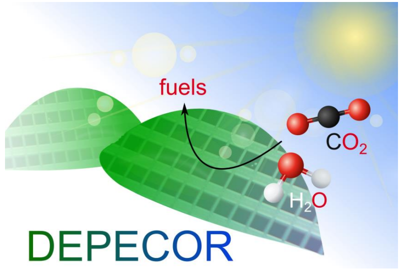


©Matthias M. May



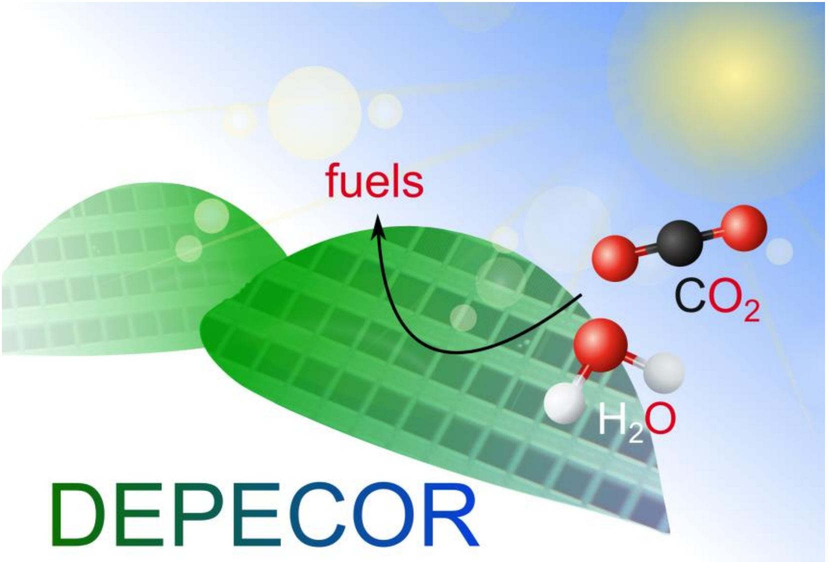
Aims:

- realization of an “**artificial leaf**” in form of a multi-absorber structure,
- a **demonstrator** to efficiently reduce CO_2 through non-assisted, direct, **solar-driven photoelectrocatalysis**
- conversion into **hydrocarbons** as storable energy sources.

The SPIRIT of science TECHNISCHE UNIVERSITÄT ILMENAU

Advantages of Photoelectrochemical Devices

- **No electric circuitry**, direct contact with electrolyte
- **No need of** balance of **2 separate systems**
- Integration can **reduce systems costs**
- **Thermodynamically** and **dynamically** more **favorable**
- **Heat accelerates** reactions – in PV heat degrades PV performance
- Lower current densities, larger spectrum of **less precious catalysts** applicable
- **Scalable** at will
- …….



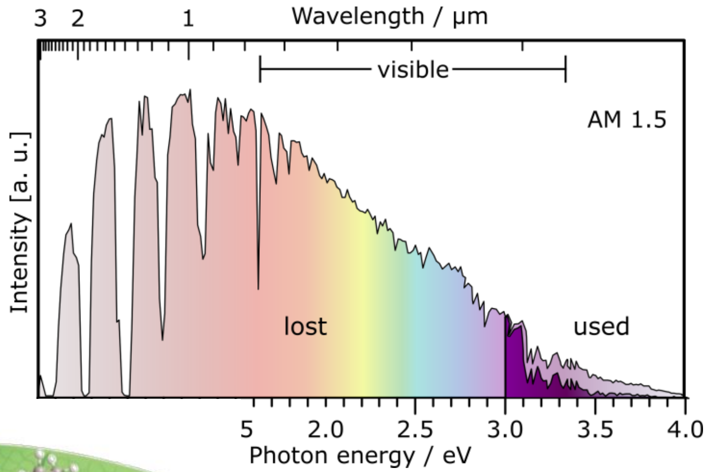
… an artificial leaf

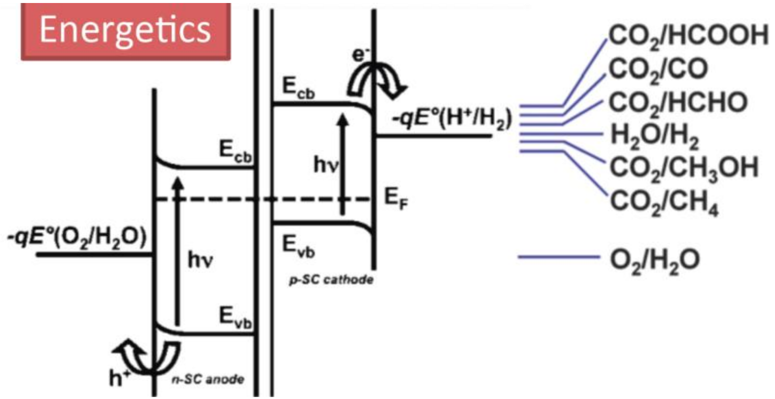
How to realize the “artificial leaf” - Photoelectrochemical cell structure

- **Photo-absorbers**
- **Metal-oxide protective layers**
- **Electro-catalysts**
- **Prototype design**

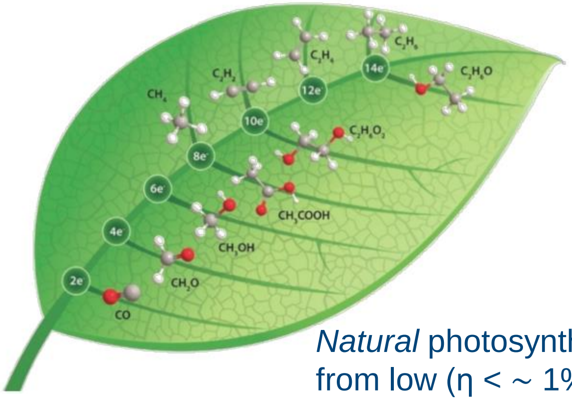
High potential needed ->

Band gap > ~ 3V required





E^0 - Nernst potential vs. Normal Hydrogen Electrode at 25 °C and 1 atm gas pressure, pH=7



Natural photosynthesis suffers from low (η < ~ 1%) efficiency

➡ **not efficient** ! with single-junction photo-absorber

Xie et al., *Chemical Communications* **2016,** *52* (1), 35
Walter et al., *Chemical Reviews* **2010,** *110* (11), 6446

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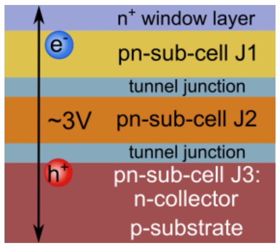

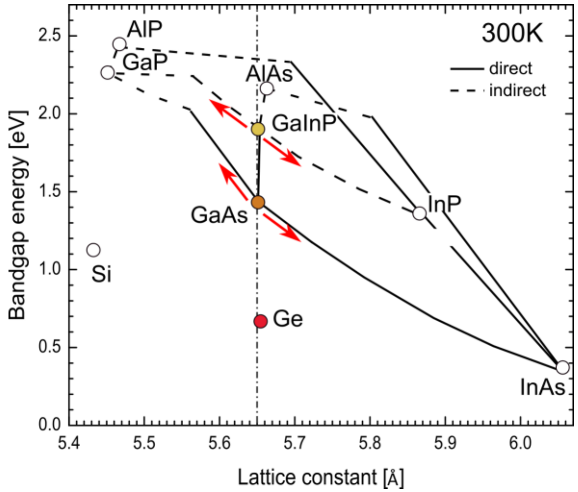

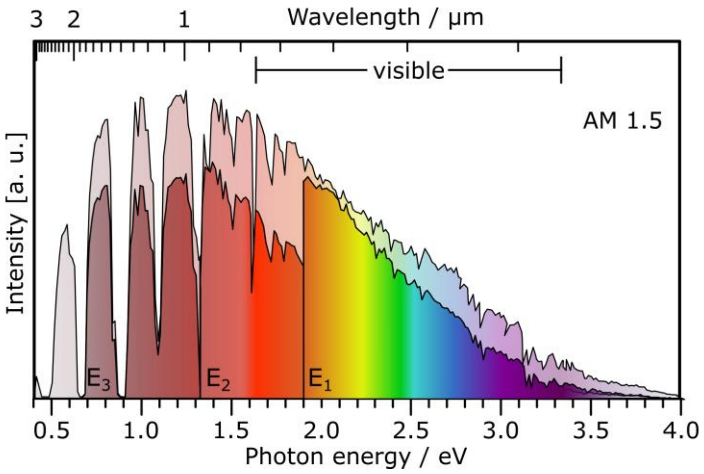

- **multi-absorbers** are required
- high **efficiency** and **optimal use** of solar photons
- III-V materials - **world-record** efficiencies
- **tunable** bandgaps

M. M. May, …, T. Hannappel, Nat. Commun. 6 (2015) 1
W. H. Cheng, … T. Hannappel et al., ACS Energy Lett. 3 (2018) 1795
J. F. Geisz et al., Nat. Energy 5 (2020) 326

How to realize the "artificial leaf" - Photoelectrochemical cell structure

- **Photo-absorbers**
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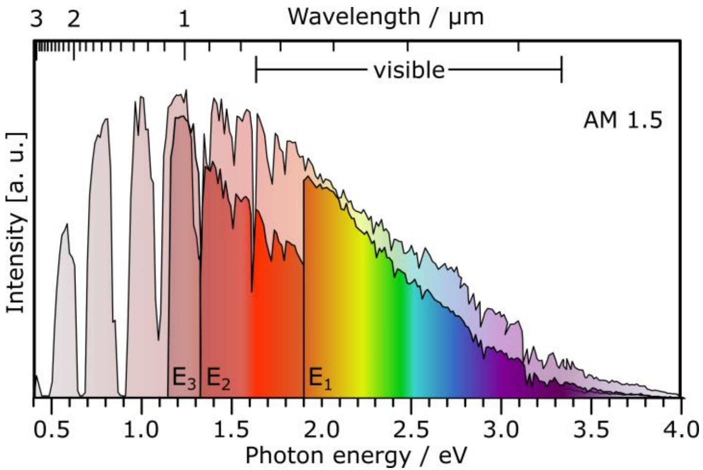

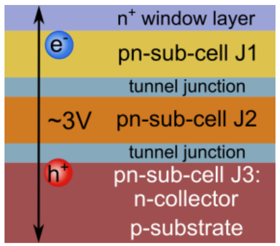

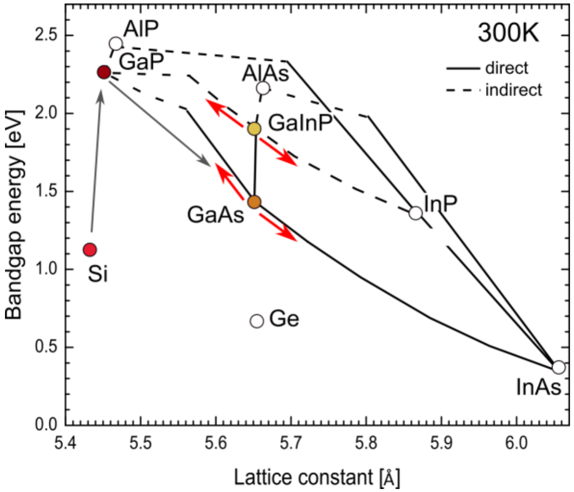

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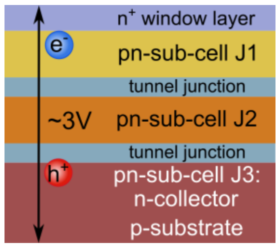
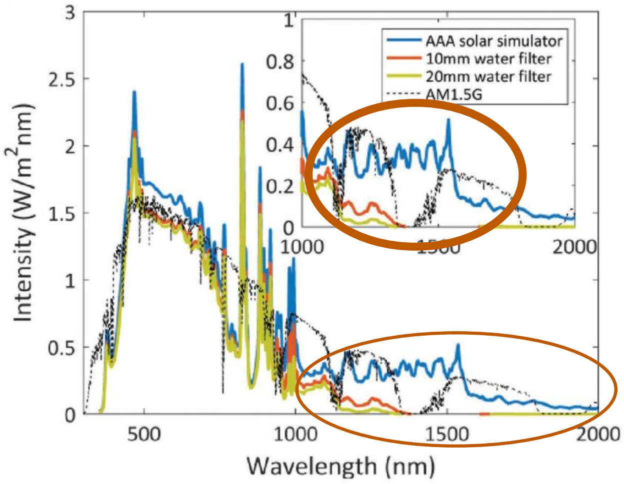
- Si – significant **costs reduction**

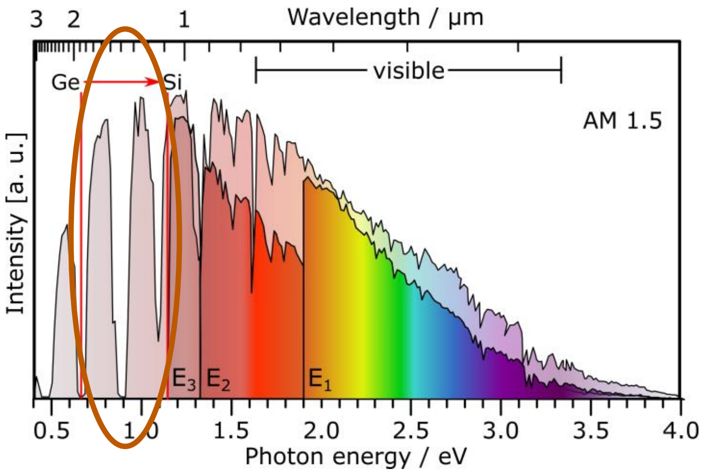
How to realize the “artificial leaf” - Photoelectrochemical cell structure

- **Photo-absorbers**
- **Metal-oxide protective layers**
- **Electro-catalysts**
- **Prototype design**



the majority of the infrared light is absorbed by the aqueous electrolyte





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- III-V materials - **world-record** efficiencies
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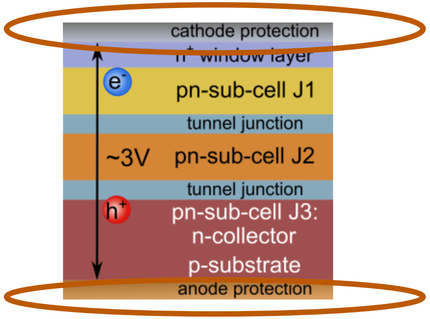
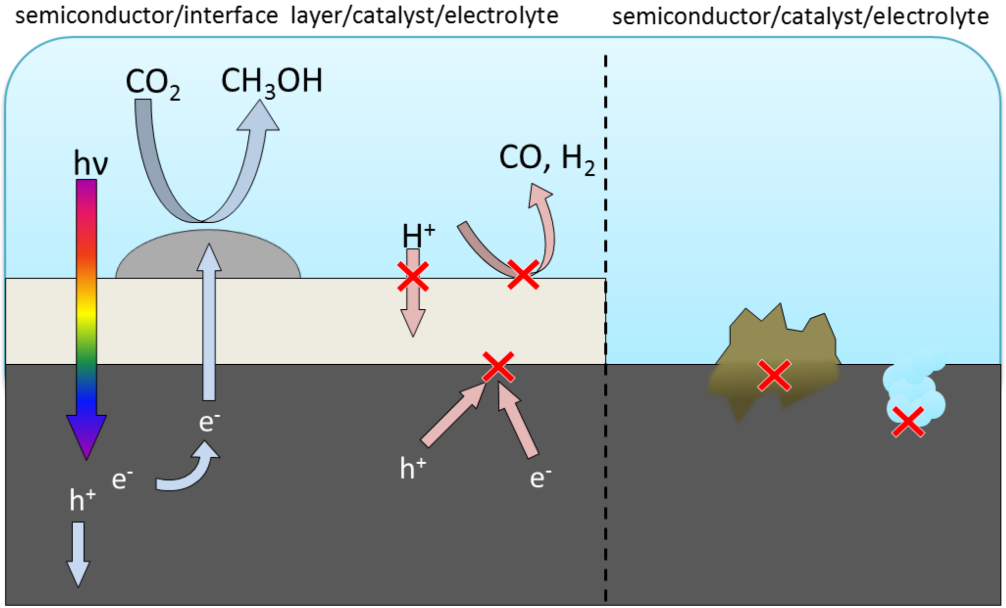
- Si – significant **costs reduction**

Fig. taken from: K. A. Walczak et al., Adv. Energy Mater. 7 (2017) 1602791

How to realize the “artificial leaf” - Photoelectrochemical cell structure

- Photo-absorbers
- Metal-oxide protective layers
- Electro-catalysts
- Prototype design





Promoting:

- Selective catalysis
- Carrier transport
- Photovoltage generation

Inhibiting:

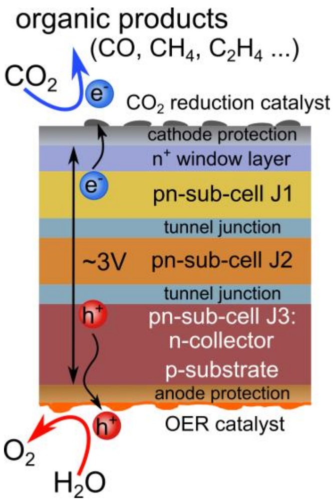
- Carrier recombination
- Proton migration
- Side-product formation

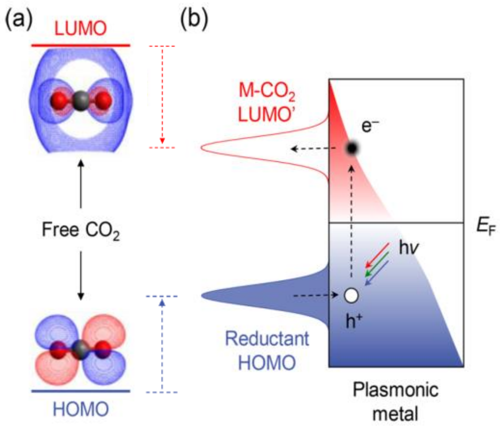
Eliminating:

- Corrosion
- Undesired material interactions

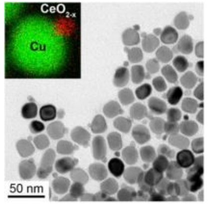
How to realize the “artificial leaf” - Photoelectrochemical cell structure

- **Photo-absorbers**
- **Metal-oxide protective layers**
- **Electro-catalysts**
- **Prototype design**





Catalysts:
Ag, Cu, Sn



- Highly selective to promote CO_2 reduction
- Efficiency / activity
- Transparency
- Plasmonic effects enhance Fischer-Tropsch reactions (use of hot electrons)
- Shape, site and size of the nanoparticle will also influence the CO_2 electrochemical reaction

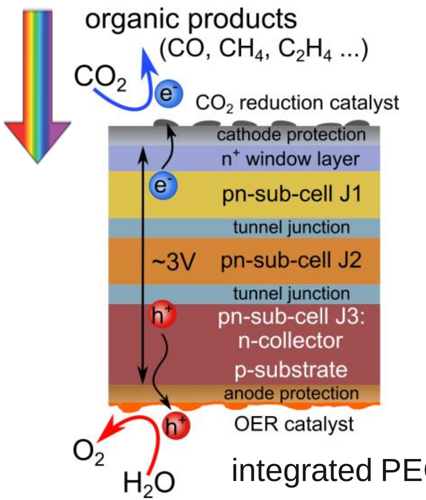
Jain et al., ACS Energy Lett. 2 (2017) 2058
Buonsanti et al., JACS 141 (2019) 2490

How to realize the “artificial leaf” - Photoelectrochemical cell structure

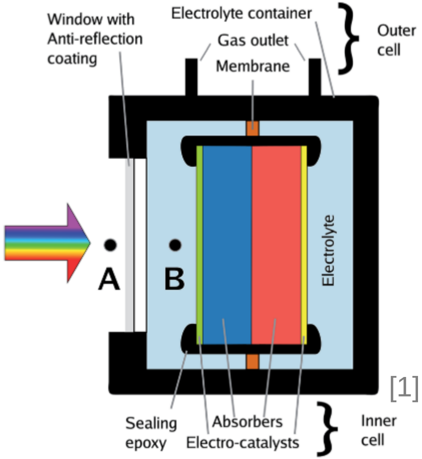
- **Photo-absorbers**
- **Metal-oxide protective layers**
- **Electro-catalysts**
- **Prototype design**

Different designs must be considered:

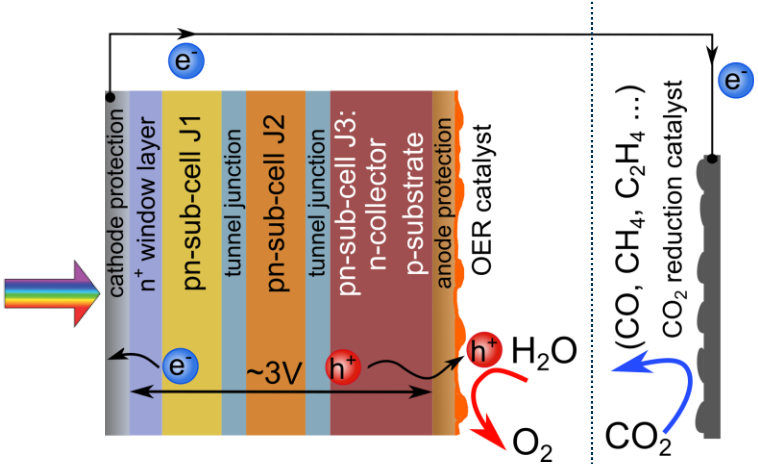
- Ideally - an integrated device
- pH of solution impacts the product development and problem of product cross-over
- Problem of transparency of the catalyst



integrated PEC cell



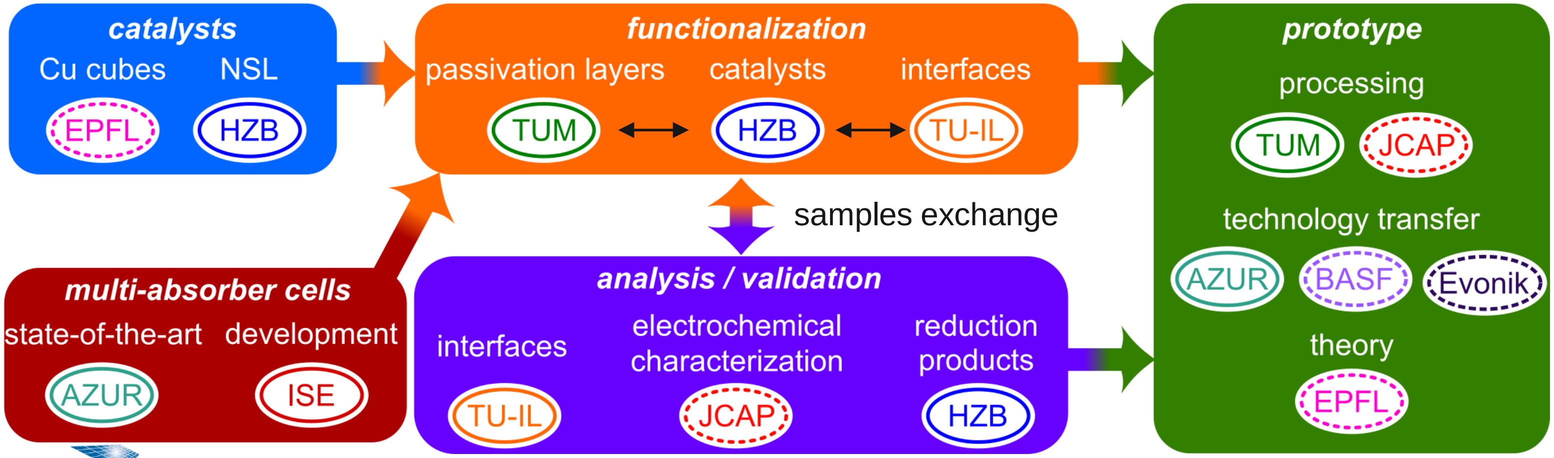
membrane

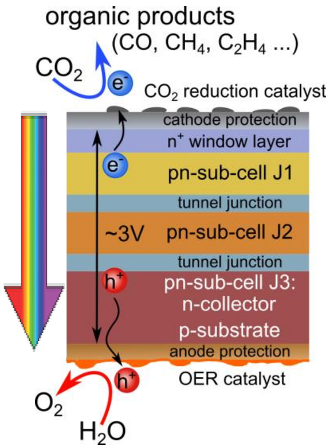


wired system with or without membrane

[1] M. M. May Sustainable Energy Fuels 1 (2017) 492

Organization of collaboration





Guidance by industrial advisory board

Goal: stable and efficient device **prototype** for CO_2 reduction

Long-term / short-term scientific visits at
JCAP in the USA and the EPFL in Switzerland were not possible due to the COVID travel restrictions.

DEPECOR Team

III-V photoabsorbers: *in situ* surface control

- **Photo-absorbers**

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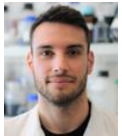
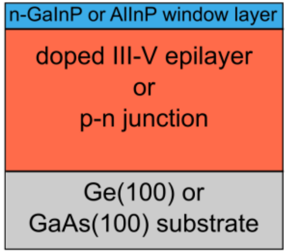
T. Hannappel


D. Ostheimer

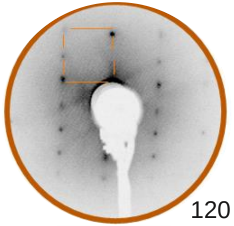

M. A. Zare Pour


A. Paszuk

group-V or III-rich atomically ordered surface

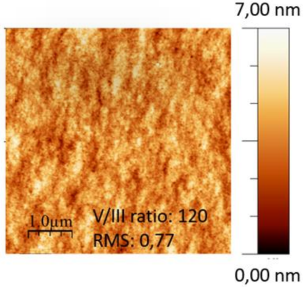


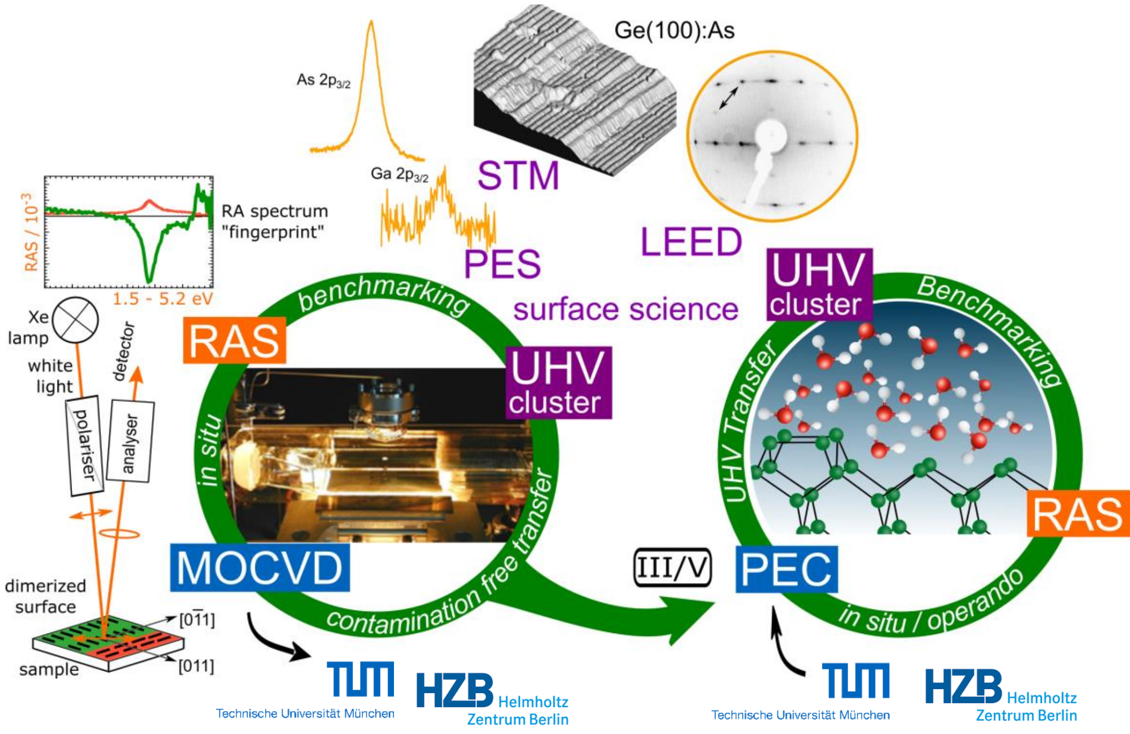
III-V half-cells



(2x1) InGaP surface grown on Ge(100)

120 eV





Fraunhofer ISE

DEPECOR Team

Performance optimization: interface engineering

- **Metal-oxide protective layers**

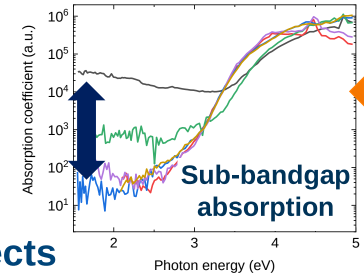
I. Sharp

O. Bienek

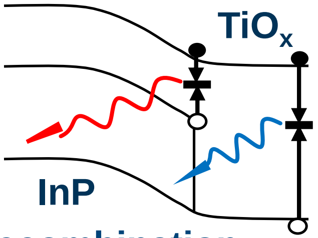
J. Kühne

Technische Universität München

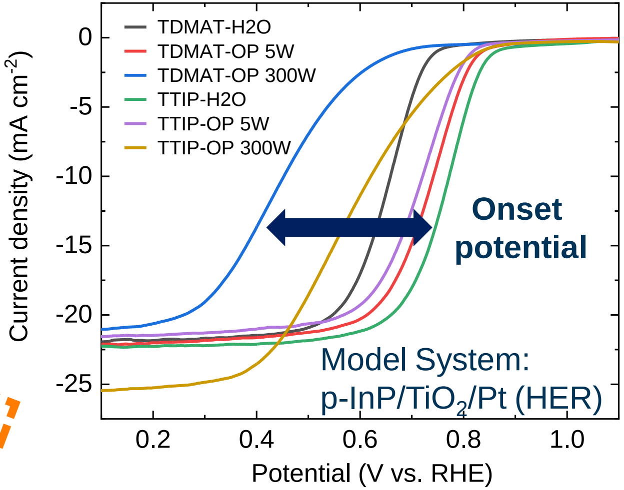
Factors influencing photoelectrochemical performance



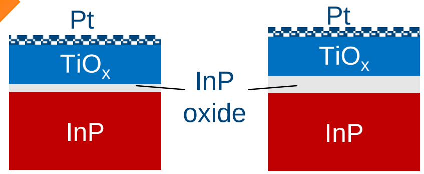
Defects



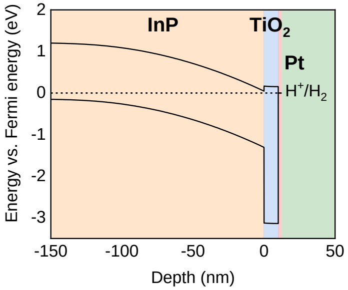
Recombination



Interfacial oxide



Interfacial energetics



DEPECOR Team

- **Electro-catalysts**

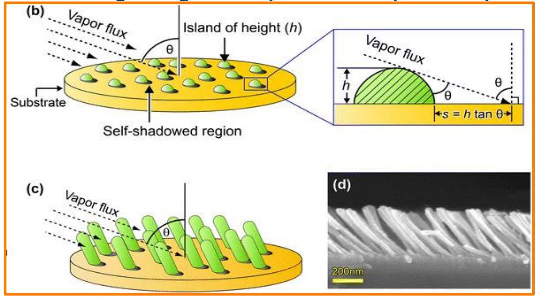
R. van de Krol   P. Bogdanoff   M. Mayer   Y.-L. Tsai   D. Aksoy

Techniques for nano-structured thin layer preparation

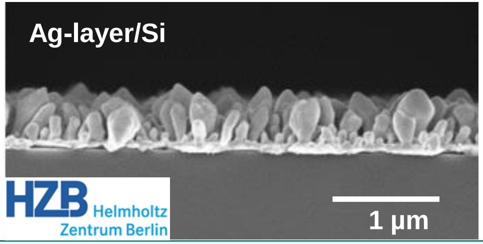
Chemical-based synthesis
- Wet-chemical preparation
- Electrodeposition

Physical deposition methods
- Glancing Angle Deposition (GLAD)
- Nanosphere Lithography (NSL)

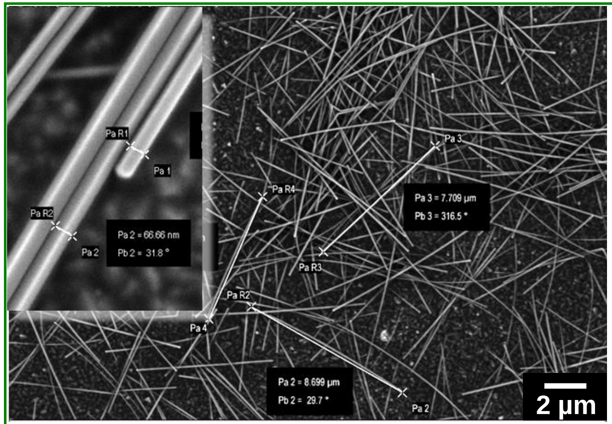
Glancing Angle Deposition (GLAD)

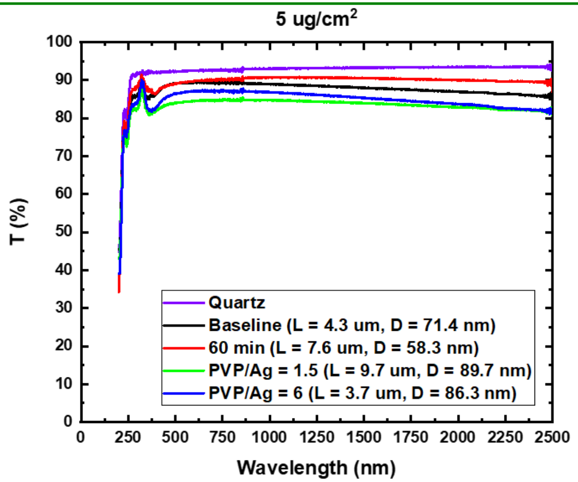


[1]



Wet-chemical Poly(vinyl pyrrolidone)-mediated synthesis





Ag-nano needles with high transparency

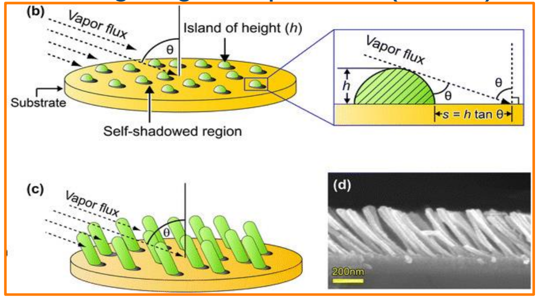
[1] *Retrieved from* Kwon et. al, *Nanoscale Res Lett* 10 (2015) 369

DEPECOR Team

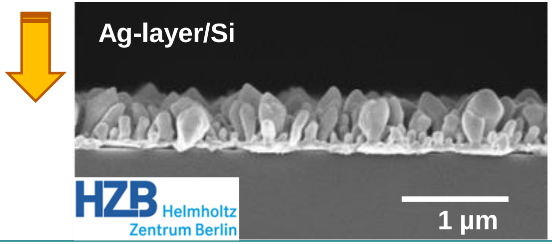
- **Electro-catalysts**

R. van de Krol | P. Bogdanoff | M. Mayer | Y.-L. Tsai | D. Aksoy

Glancing Angle Deposition (GLAD)



[1]



Techniques for nano-structured thin layer preparation

Chemical-based synthesis

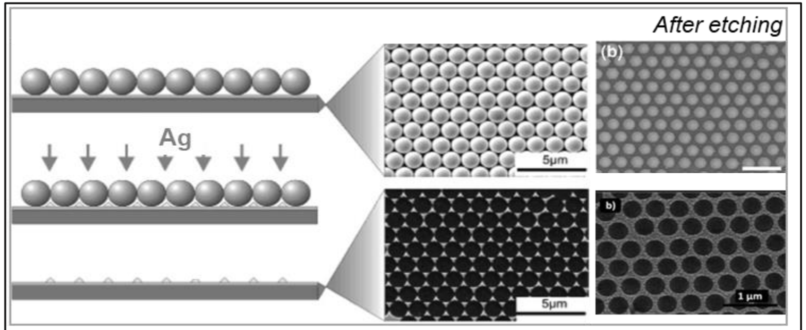
- Wet-chemical preparation
- Electrodeposition

Physical deposition methods

- Glancing Angle Deposition (GLAD)
- Nanosphere Lithography (NSL)

in planning:

- Nanosphere Lithography (NSL)



From KSV-NIMA web site

- study CO_2RR activity of the differently deposited nano-catalysts

[1] *Retrieved from* Kwon et. al, *Nanoscale Res Lett* 10 (2015) 369

DEPECOR Team

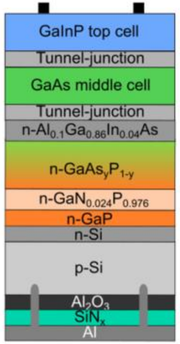
- ## III-V/Si photoabsorbers

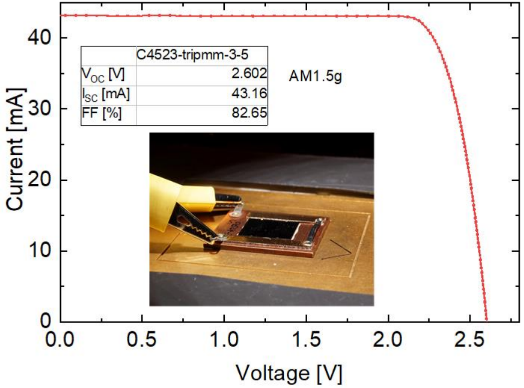
Fraunhofer ISE


F. Dimroth


M. Feifel

- New cell structure must be established to achieve the high photovoltage



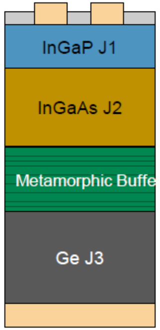


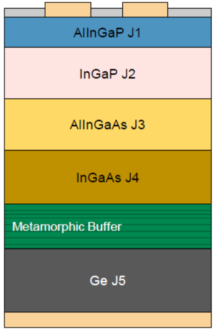
- ## III-V/Ge or GaAs test solar cells

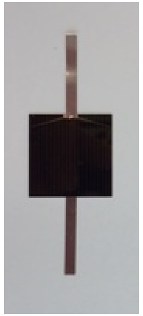
AZURSPACE SOLAR POWER GMBH

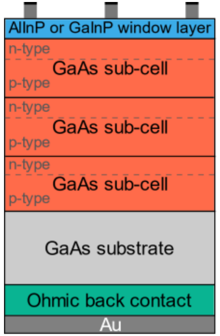

G. Strobl


V. Khorenko









DEPECOR Team – associated partners

H.A. Atwater

- support in the catalysts development,
  products quantification, membrane,
  models of mass transport of CO_2 to the active surfaces,
  device testing

R. Buonsanti

S. Haussener

- investigate the activity of specific Cu catalysts
  support in the modeling of the prototype

F. Menzel

- advise on the prototype development regarding the technology transfer and commercial, relevant products

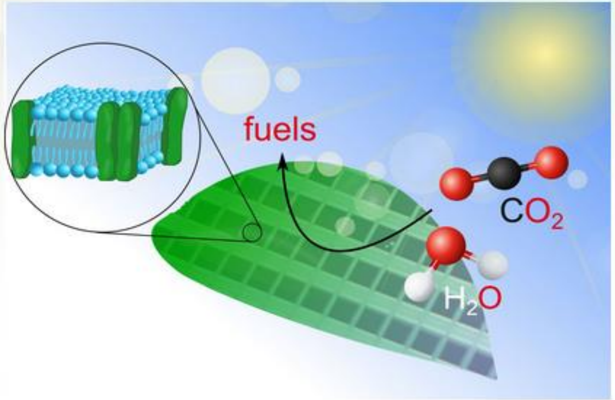
S. Bräuninger

Student and PI exchange was planned previously in long- and short-term scientific visits at JCAP in the USA and the EPFL in Switzerland.
Not possible due to the pandemic, therefore …..

US-German workshop series

co2-utilization.net

US-German workshop series on artificial photosynthesis



Artificial Photosynthesis (AP) to generate useful chemicals and materials using only components of air and sunlight as inputs is a dream of visionaries and an active area of research. The AP research communities in Germany and the United States have many overlapping and complementary interests, and fruitful collaborations between them will help accelerate progress in the field. In the summer of 2020, a workshop sponsored by the BMBF in Germany and the DOE in the United States examined areas of opportunity for joint work, and recommended that an ongoing meeting series be launched to promote new connections between the scientific and engineering communities in the two countries.

This meeting series is now launched, organized by the German CO_2-WIN consortium and a US-German steering committee.

The kick-off workshop took place on 25 May 2021. Below you will find the agenda and a link to register for the free event series. Registration will enable you to receive notices for future events.

Kick-off: May 25th

Next workshops: June 29th and July 27th or August 3rd

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.

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Thank you for your attention