Photon Management Enables High Efficiency Photovoltaics

Henning Helmers

Fraunhofer Institute for Solar Energy Systems ISE

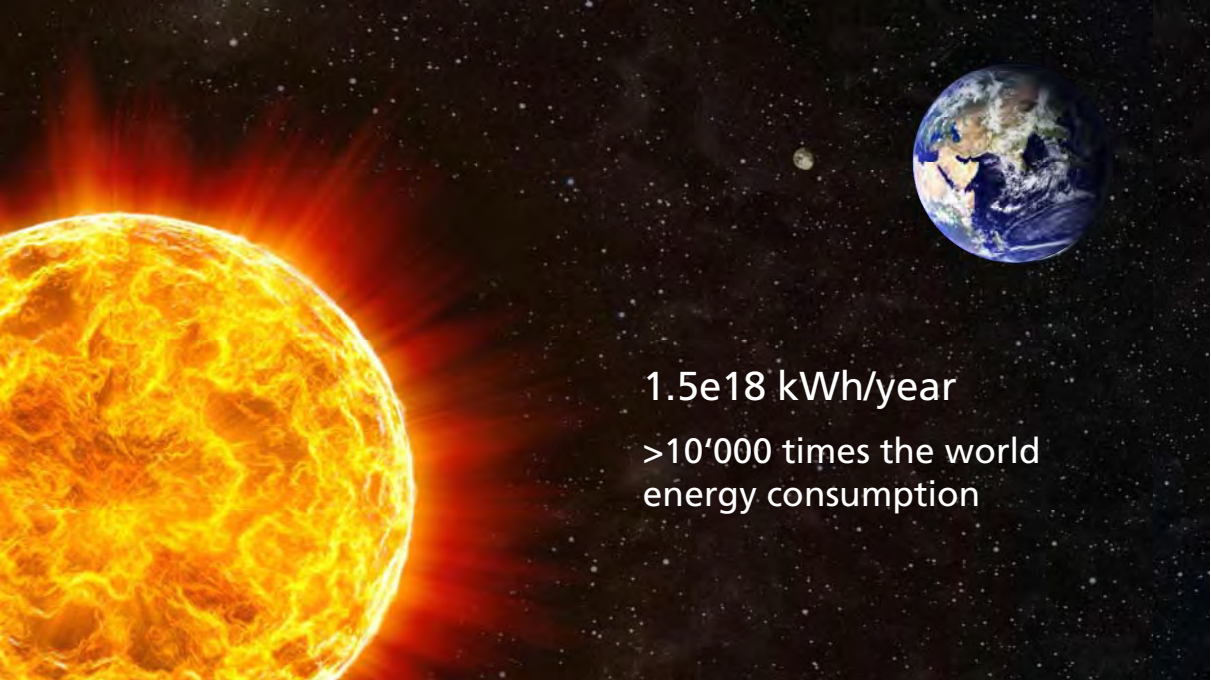
4th Fraunhofer Symposium on
„Digital Photonics made in Germany“

Tokyo, 09.10.2019

www.ise.fraunhofer.de

December 12, 2015
Paris, France

uissou – MEDDE / SG COP21


1.5e18 kWh/year
>10‘000 times the world energy consumption

Silicon-based Photovoltaics

Solarsiedlung, Stadtteil Vauban, Freiburg, Germany

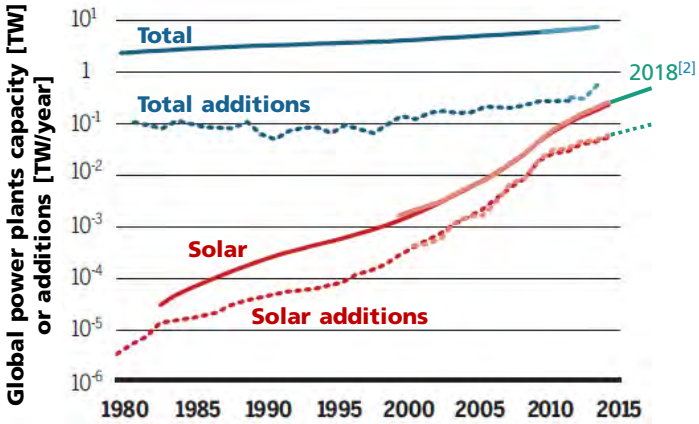
Picture: Rolf Disch SolarArchitektur, www.rolfdisch.de

Silicon-based Photovoltaics: Top 25 Operational Solar PV Plants in Japan

Pictures: https://asia.solar-asset.management/top-25-largest-projects

Terawatt-scale Photovoltaics: Trajectories and Challenges [1]

- Solar capacity is growing exponentially for decades
- 2018, solar PV capacity additions passed 100 GW mark
- Exponential growth rate of solar substantially greater than growth in electricity demand
- Request to technology
  - Further cost reduction
  - Efficiency increase (=reduced balance of system cost)



[1] NM Haegel, R Margolis, T Buonassisi, D Feldman, A Froitzheim, R Garabedian, M Green, S Glunz, HM Henning, B Holder, I Kaizuka, B Kroposki, K Matsubara, S Niki, K Sakurai, RA Schindler, W Tumas, ER Weber, G Wilson, M Woodhouse, S Kurtz, Science 356(6334), 2017. DOI: 10.1126/science.aal1288
[2] REN21. *Renewables 2019 Global Status Report*, 2019. ISBN 978-3-9818911-7-1

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Silicon Based Solar Cells: State of the Art

Si single-junction solar cell

Kaneka IBC record cell [#]
η=26.7%

[#] Yoshikawa, et al., Nature Energy 2, 2017.
[§] Polman, et al., Science 352, 2016 (latest values: www.lmpv.nl/SQ).

High-efficiency Photovoltaics
How to Make Better Use of the Broad Band Solar Spectrum?

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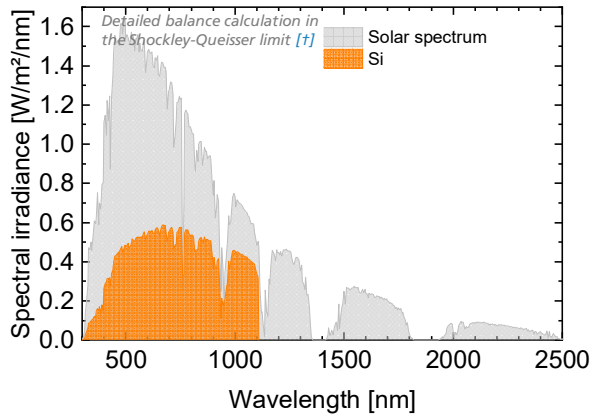

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High-efficiency Photovoltaics

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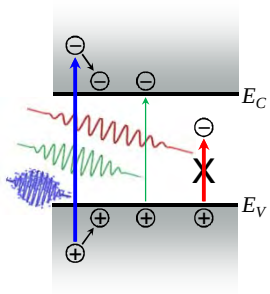
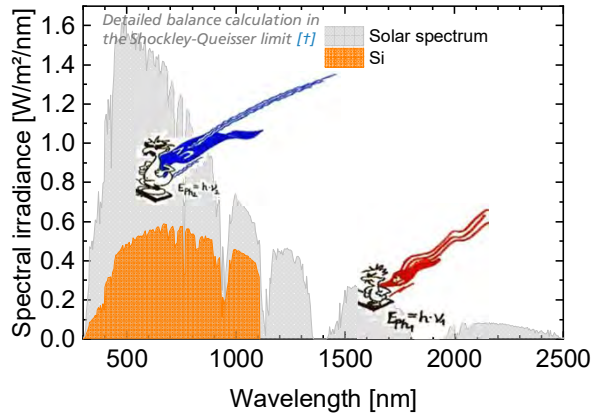


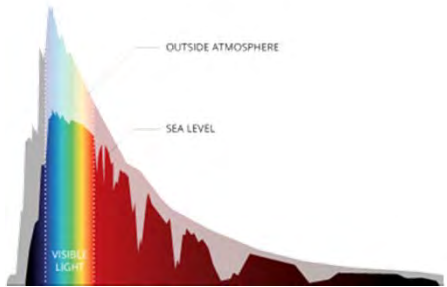


[†] Shockley and Queisser, J Appl Phys 32(3), 1961.

High-efficiency Photovoltaics
Enabled by Photon Management

- Manipulate the spectrum [1,2,3,4]

- Adapt the receiver material



Fondriest Environmental "Solar Radiation and Photosynethically Active Radiation." Fund Environ Meas. 2014.

[1] Götzberger, Greubel, Appl Phys 14, 1977: Luminescent concentrator
[2] Young, Appl Opt 5(6), 1966: Solar-pumped fiber laser
[3] Harder and Würfel, Semicond Sci Tech 18, 2003: Thermophotovoltaics
[4] Trupke, Green, Würfel, J Appl Phys 92, 2002: Up- and down-conversion of photons

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High-efficiency Photovoltaics
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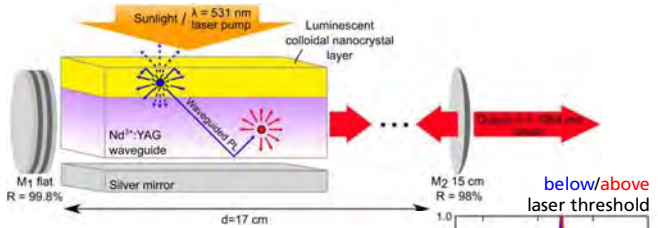

Reusswig, Nechayev, Scherer, Hwang, et al, Scientific Reports 5, 2015.

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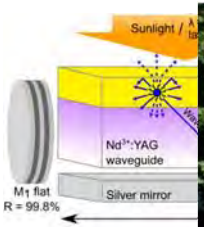

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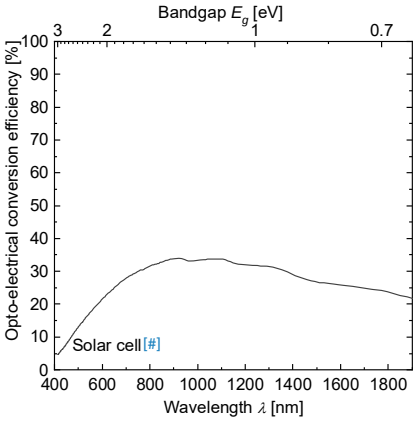
Photovoltaic Laser Power Converters
Theoretical Limit

Detailed balance calculation in the Shockley-Queisser limit for a single-junction PV cell



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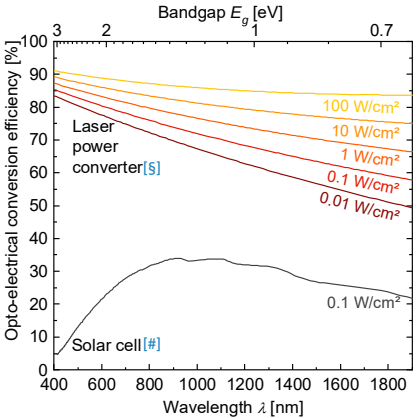

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[§] Bett, Dimroth, Löckenhoff, Oliva, Schubert, Proc IEEE PVSC, San Diego, 2008.

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Photovoltaic Laser Power Converters

Photon Management by Bandgap Engineering: III-V Compound Semiconductors

III	IV	V
$_{5}$B	$_{6}$C	$_{7}$N
$_{13}$**Al**	$_{14}$Si	$_{15}$**P**
$_{31}$**Ga**	$_{32}$Ge	$_{33}$**As**
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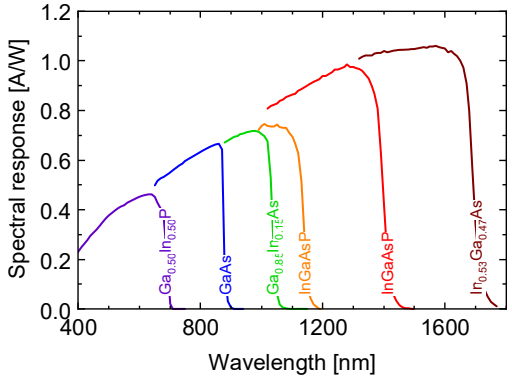
$_{81}$Tl	$_{82}$Pb	$_{83}$Bi



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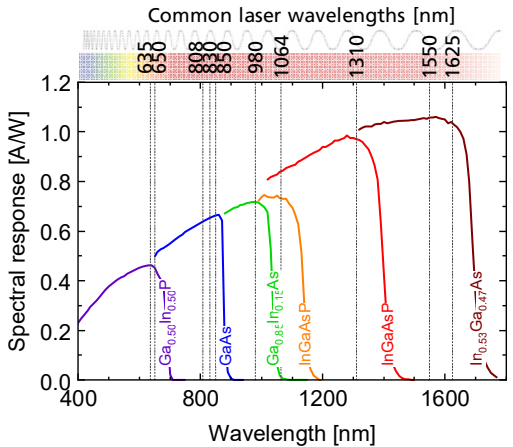
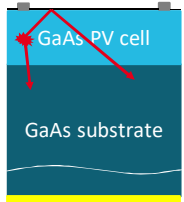
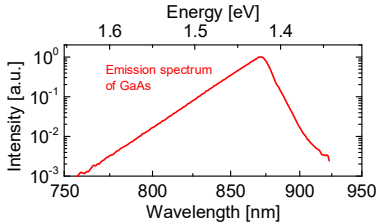


Photovoltaic Laser Power Converters
Light Trapping and Photon Recycling

- Cell on substrate: Emitted photons from the absorber are lost into the substrate





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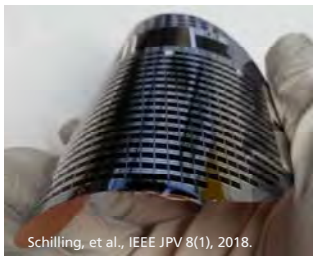
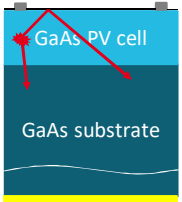
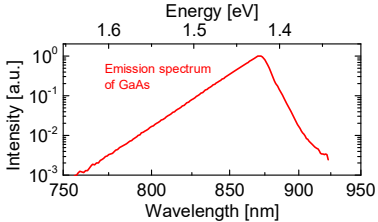
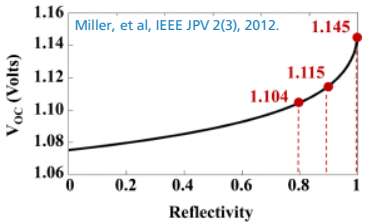
- Back mirror: Light is trapped inside the absorber → increased carrier concentration → boost voltage („photon recycling“) [#]









[#] Miller, et al., IEEE JPV 2(3), 2012. | Walker, et al., IEEE JPV 5(6), 2015.

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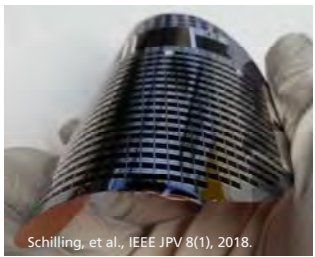
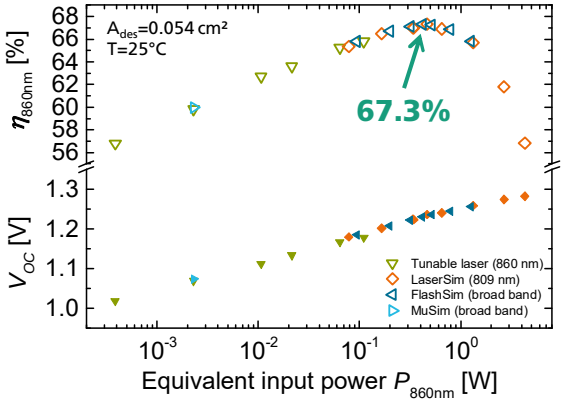

Schilling, et al., IEEE JPV 8(1), 2018.

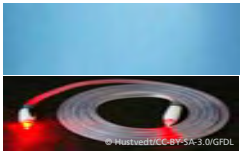


Helmers, Höhn, Lackner, López, et al., Proc OWPT, Yokohama, 2019.

Power (and Data) by Light

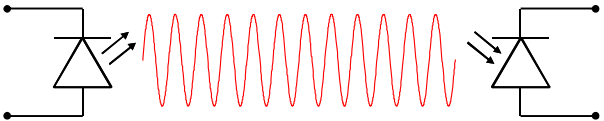
Optical Power Transmission – An Enabling Technology

Laser



Free space/
optical fiber

PV cell



Galvanic
isolation

Electro-magnetic
interference

Lightning
protection

Weight
reduction

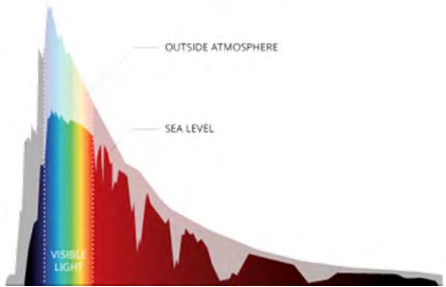
Explosion
protection

Wireless
power

Helmers, Lackner, Siefer, Oliva, et al., Proc 32nd EU PVSEC, Munich, 2016.
Helmers, Höhn, Lackner, López, et al., Proc OWPT, Yokohama, 2019.

High-efficiency Photovoltaics
Enabled by Photon Management

- Manipulate the spectrum
- Adapt the receiver material
  - Multi-junction solar cells [1,2]



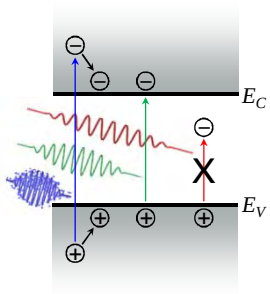
Fondriest Environmental "Solar Radiation and Photosynethically Active Radiation." Fund Environ Meas. 2014.

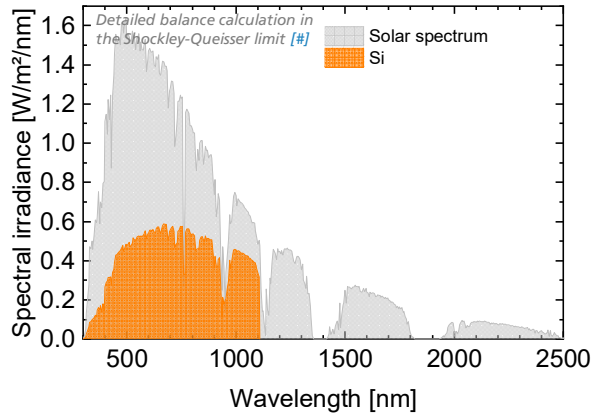
[1] Henry, J Appl Phys 51, 1980.
[2] Philipps, Dimroth, Bett, in: McEvoy's Handbook of Photovoltaics, Kalogirou (Ed.), London: Academic Press, 2018.

High-efficiency Photovoltaics

How to Make Better Use of the Broad Band Solar Spectrum?

Si single-junction solar cell





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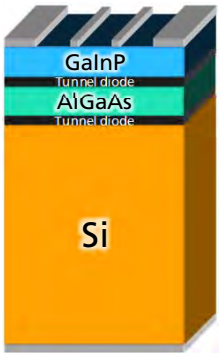
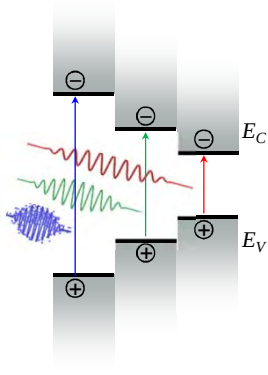
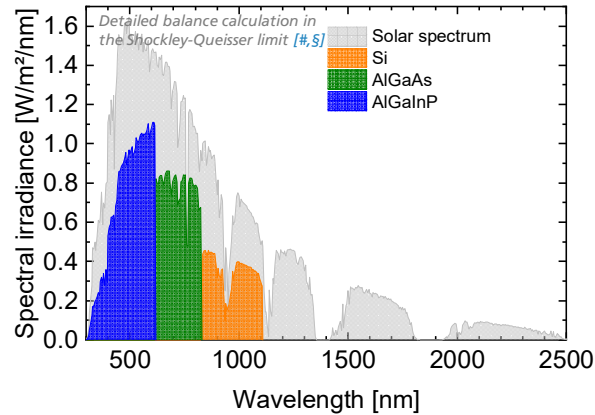


III-V/Si tandem solar cell





[#] Shockley and Queisser, J Appl Phys 32(3), 1961.
[§] Létay and Bett, Proc 17th EU PVSEC, Munich, Germany, 2001.

High-efficiency Photovoltaics
Si-Tandem Technology Expected

ITRPV International Technology Roadmap for Photovoltaic VDMA

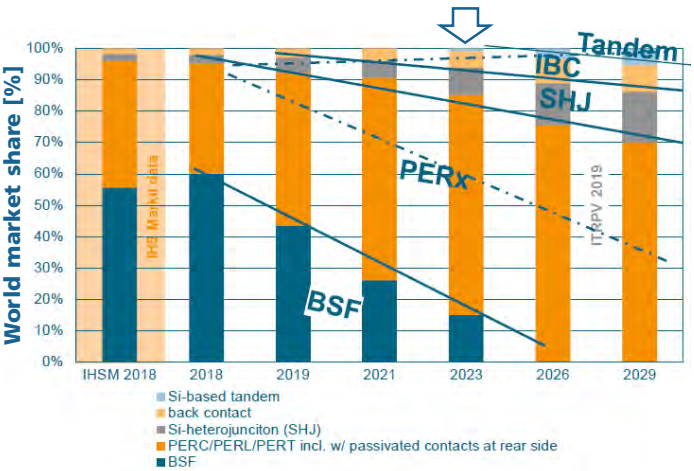
ITRPV 10th edition 2019 - report release and key findings

Markus Fischer

PV CellTech Conference, March 13 2019

Penang, Malaysia

https://itrpv.vdma.org/



Fischer, PV CellTech Conf., 2019. https://itrpv.vdma.org/

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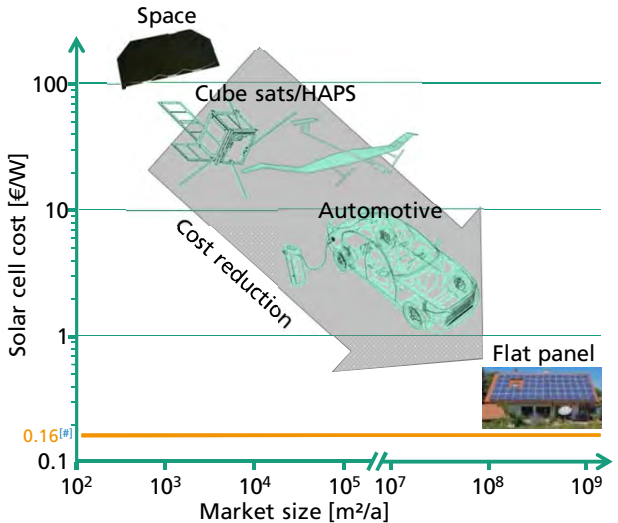
High-efficiency Photovoltaics
Present and Future Markets

Cube sats / high altitude pseudo satellites

Solar electric vehicles



[#] Mono PERC cell, high, http://pvinsights.com/ (27.09.2019)

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III-V/Si Tandem Solar Cells
Fabrication Approach: Wafer Bonding Route

Cariou, Benick, Feldmann, Höhn, et al, Nature Energy 3, 2018.

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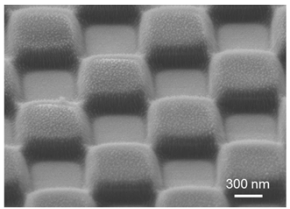
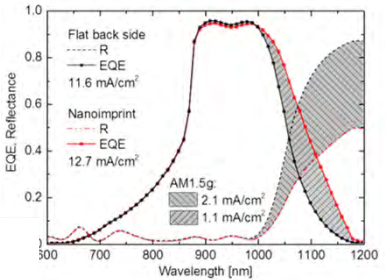
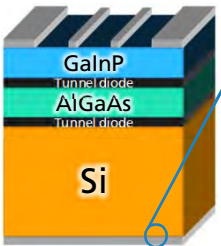
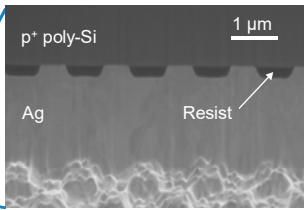
III-V/Si Tandem Solar Cells
with Rear-side Photonic Grating

- Photonic light trapping realized by nanoimprint lithography
- Boost in photo current of Si subcell (indirect semiconductor absorber)









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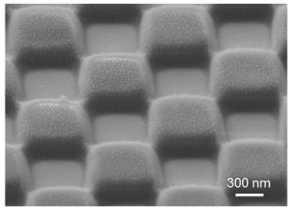
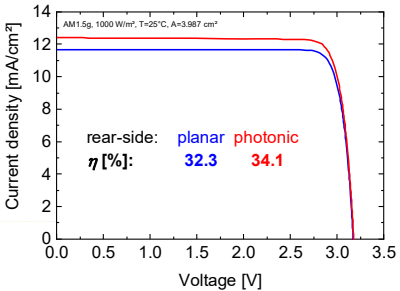
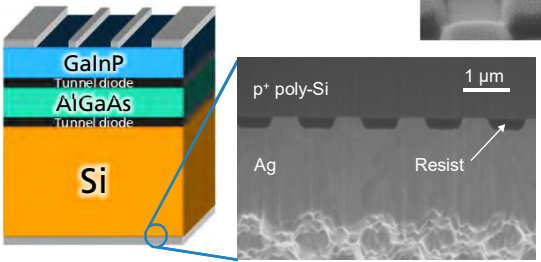




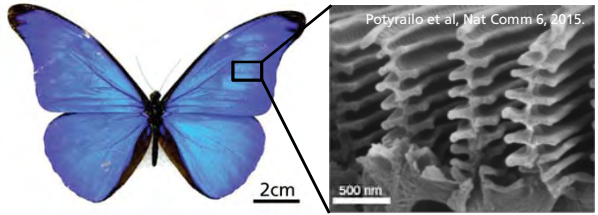


Cariou, Benick, Feldmann, Höhn, et al, Nature Energy 3, 2018.
Fraunhofer ISE, press release #22, 28.09.2019.

Bio-inspired Photonic Structures for Integrated Photovoltaics
Morpho-Color®

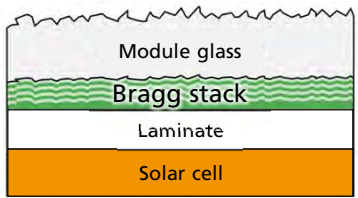
Idea:

- Morpho butterfly:
  bright, angle independent color
  originated from a 3D photonic structure



Realization:

- Morpho effect reproduced by Bragg stack on
  a structured substrate



Höhn, Kroyer, Bläsi, Kuhn, Hinsch, Patent: WO/2018/154045.

Bio-inspired Photonic Structures for Integrated Photovoltaics:
Morpho-Color® PV Modules for Building Integration

- Narrow band reflection:
  - Bright color appearance
  - Only 7% relative efficiency reduction
- Various colors possible
- Only module glass is modified

➔ Standard solar cells and lamination processes can be used

Demonstrator modules: 1.09 x 1.12 m^2

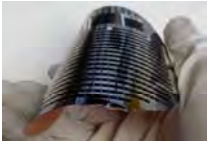
Höhn, Kroyer, Bläsi, Kuhn, Hinsch, Patent: WO/2018/154045.

Bio-inspired Photonic Structures for Integrated Photovoltaics:
Morpho-Color® PV Modules for Vehicle Integration

Frankfurt Motor Show (IAA), 2019

Photon Management Enables High Efficiency Photovoltaics
Summary

- Power-by-Light
  - Bandgap engineering for PV laser power converters
  - Efficiency of η_{860nm}=67.3% enabled by photon recycling
- Tandem solar cells
  - Photonic rear-side gratings enable light trapping
  - III-V/Si tandem solar cell with 34.1% efficiency demonstrated
- Photonic structures enable invisible photovoltaics
  e.g. for building and vehicle integration



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- all sponsors for financial support
- all partners
- all co-workers at Fraunhofer ISE

Federal Ministry of Education and Research

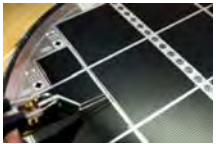
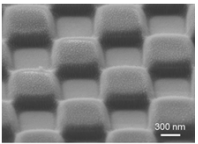
Federal Ministry for Economic Affairs and Energy

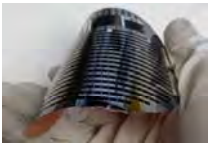
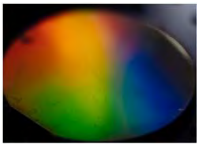
DBU Deutsche Bundesstiftung Umwelt

RLS REINER LEMOINE STIFTUNG

MARIE CURIE ACTIONS

Thank you for your Attention!

Fraunhofer Institute for Solar Energy Systems ISE

Dr. Henning Helmers, Deputy Head of Department “III-V Photovoltaics and Concentrator Technology”

www.ise.fraunhofer.de | www.III-V.de | s.fhg.de/profile-h-helmers
henning.helmers@ise.fraunhofer.de