Faculty of Engineering
School of Photovoltaic and Renewable Energy Engineering

High Efficiency Photovoltaics, Progress towards the Ultimate Limit for Solar Power Conversion

2024 UNSW-SKKU Joint Workshop : Next Generation Green Energy Technologies

Ned Ekins-Daukes

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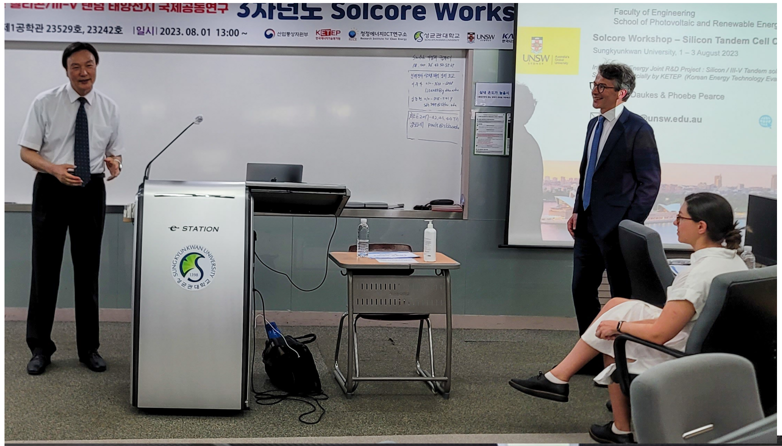
www.qpvgroup.org

EkinsNed

Silicon Tandem Modelling Workshop,

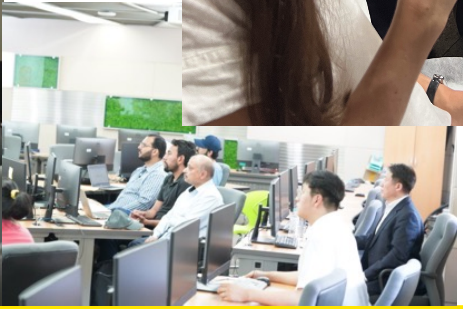
2-4 August 2023 : Sungkyunkwan University, South Korea

SUNGKYUNKWAN UNIVERSITY 1398 성균관대학교



Dr Phoebe Pearce

KETE
한국에너지기술
KOREA INSTITUTE OF ENERGY
EVALUATION AND



Workshop: Modelling solar cells in Python

Phoebe Pearce & Ned Ekins-Daukes

School of Photovoltaic and Renewable Energy Engineering (SPREE)

UNSW Sydney

free)

vember, 1 – 5 pm
ion (date TBC)
tting Python and
on your own

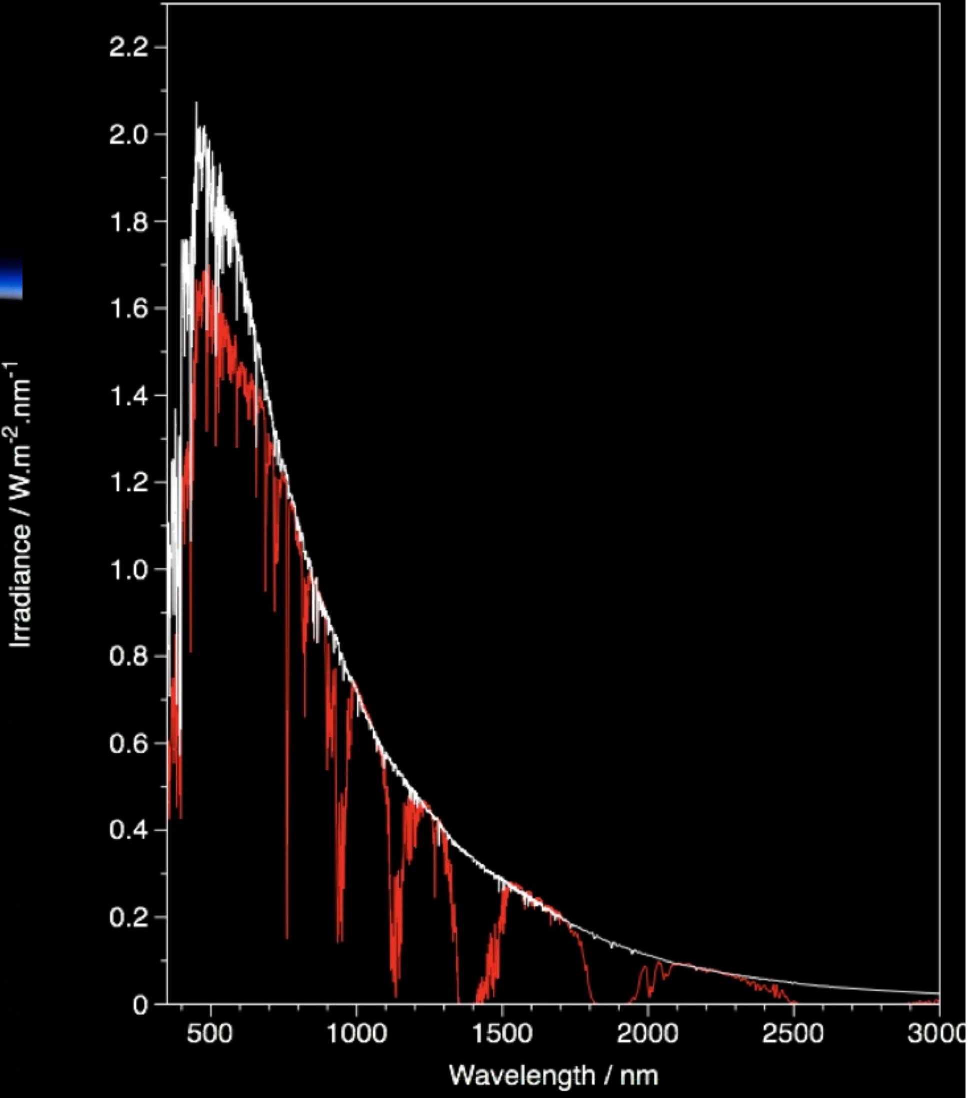
ftware requirements
e, open-source Python packages **Solcore**
d **RayFlare**, which are developed here in
REE. You can run these on your own
mputer (Windows, MacOS or Linux). While
aim to also make the code and examples
in the cloud, we encourage you to bring
ur laptop to the sessions!

ile this is not a comprehensive 'Introduction
Python' course, we encourage everyone who
nterested to attend, regardless of experience
n Python or programming.

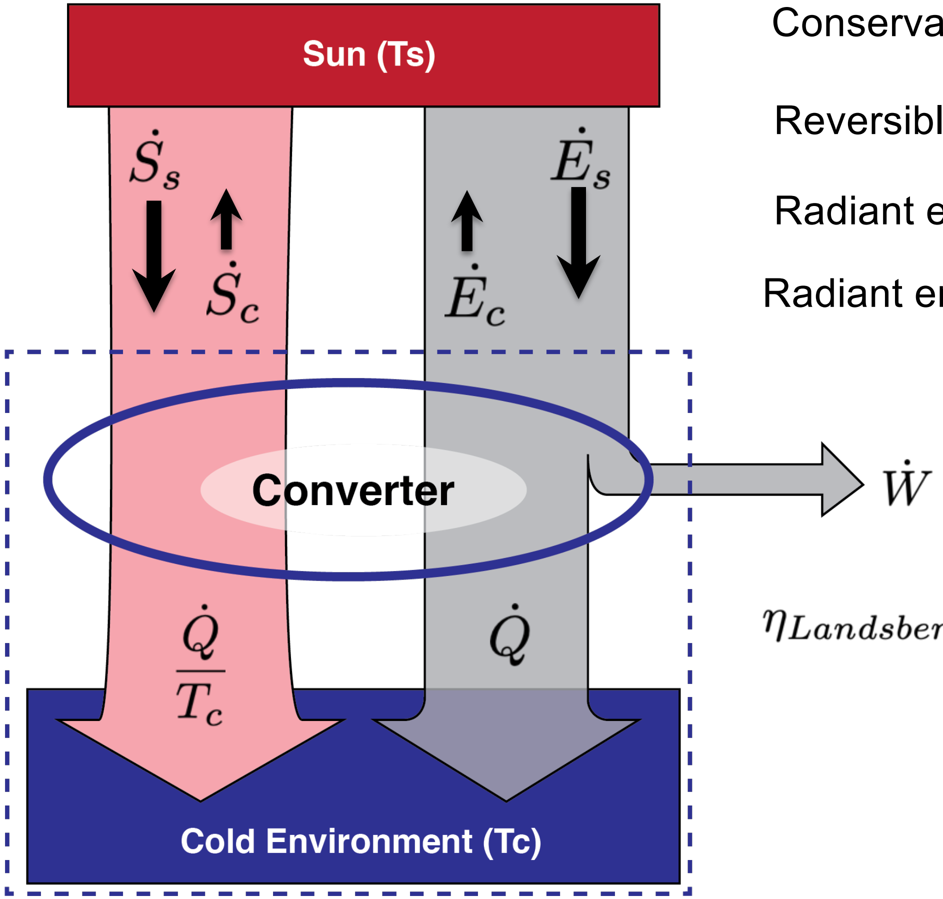
through calculation of limiting currents,
Shockley-Queisser limit) for solar cells
optical models in Solcore
lls of increasing complexity:
and GaAs) using the depletion approximation
atrix method to calculate the effect of anti-

silicon: using **ray-tracing methods** for Si with pyramid textures and a **Maxwell equation solver** for a diffraction grating
  - Cell model using a **drift-diffusion solver** for a textured Si cell
  - **III-V/Si** and **Perovskite/Si tandem cells** with light-trapping structures (pyramids, gratings, anti-reflection coatings)
- Use of the Katana computing cluster for e.g. running optimizations

https://qpv-research-group.github.io/solcore-education/


Irradiance / W.m^{-2}.nm^{-1}
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
500
1000
1500
2000
2500
3000
Wavelength / nm

Landsberg Limit for Solar Power Conversion



Conservation of Energy: $\dot{Q} + \dot{W} = \dot{E}_s - \dot{E}_c$

Reversible operation: $\dot{S}_s - \dot{S}_c = \frac{\dot{Q}}{T_c}$

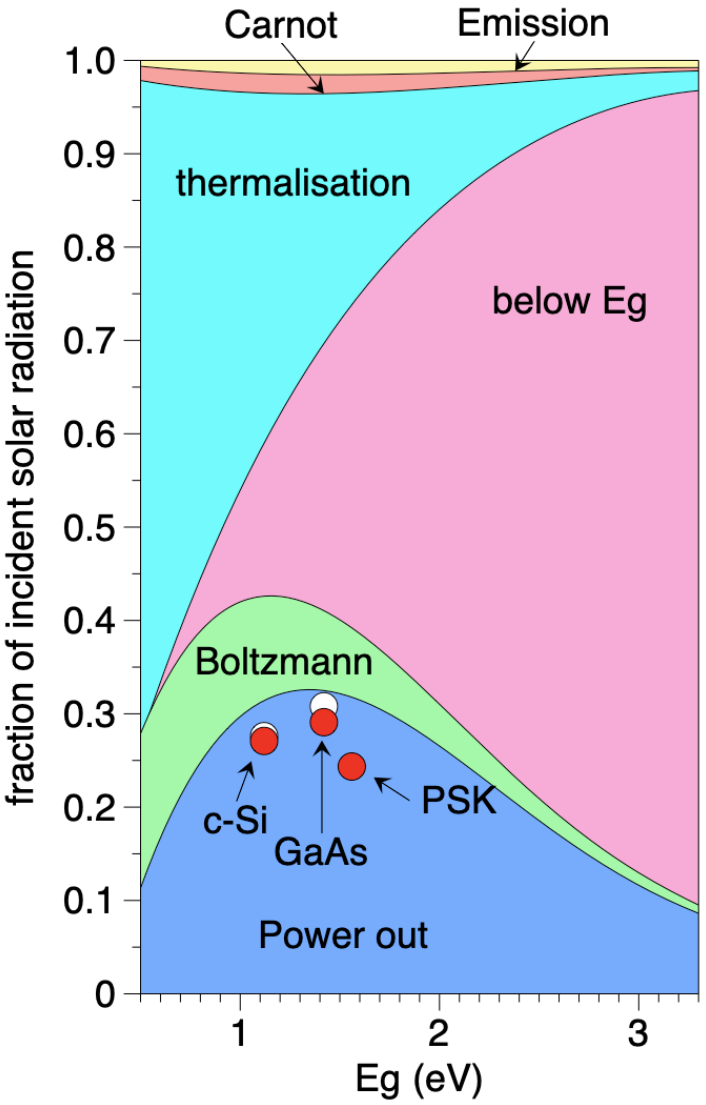
Radiant energy flux density: $\dot{E} = \sigma T^4$

Radiant entropy flux density: $\dot{S} = \frac{4}{3}\sigma T^3$

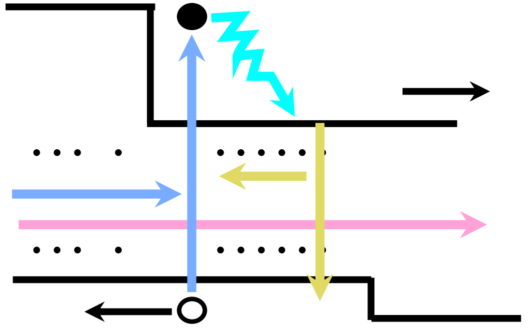
$$\eta_{Landsberg} = \frac{\dot{W}}{\sigma T_s^4} = 1 - \frac{4}{3}\frac{T_c}{T_s} + \frac{1}{3}\frac{T_c^4}{T_s^4}$$

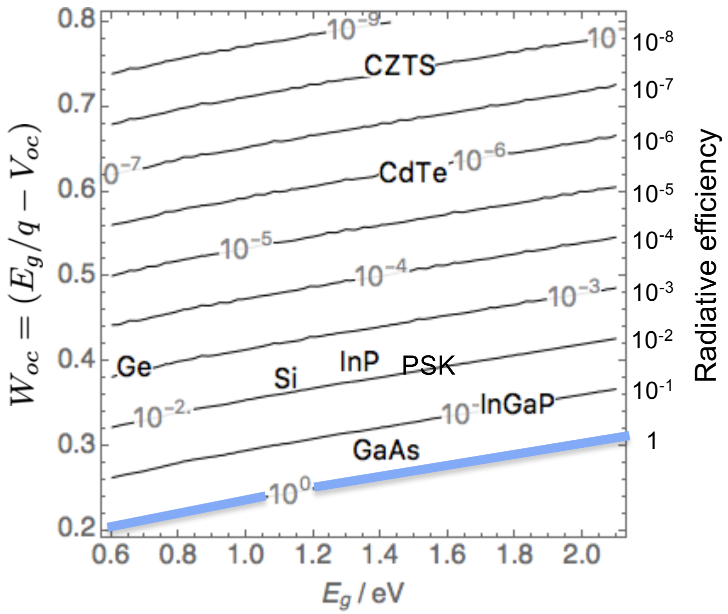
$$< \eta_{Carnot} = 1 - \frac{T_c}{T_s}$$

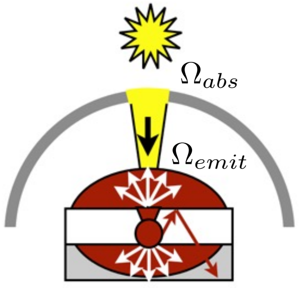
P. T. Landsberg and G. Tonge, J. Appl. Phys. 51, R1 (1980).



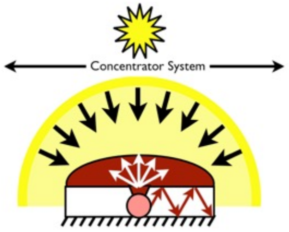
Fundamental losses in solar cells:



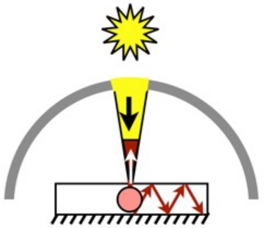




$$\Omega_{emit} >> \Omega_{abs}$$



$$\Omega_{emit} = \Omega_{abs}$$



$$qV_{max} = E_g - E_g\frac{T_A}{T_s} - kT_A \ln\left(\frac{\Omega_{emit}}{\Omega_{abs}}\right)$$

L. Hirst & N.J.Ekins-Daukes, Progress in Photovoltaics, (2011) 19: p286

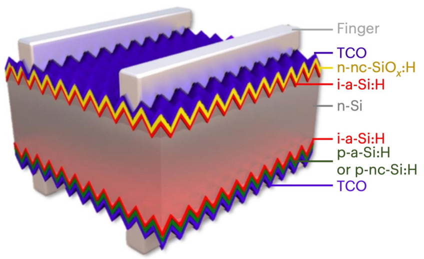
nature energy

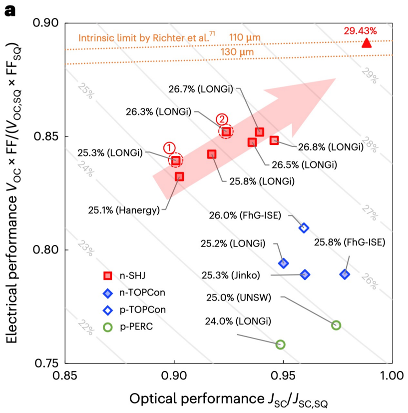
Silicon heterojunction solar cells with up to 26.81% efficiency achieved by electrically optimized nanocrystalline-silicon hole contact layers

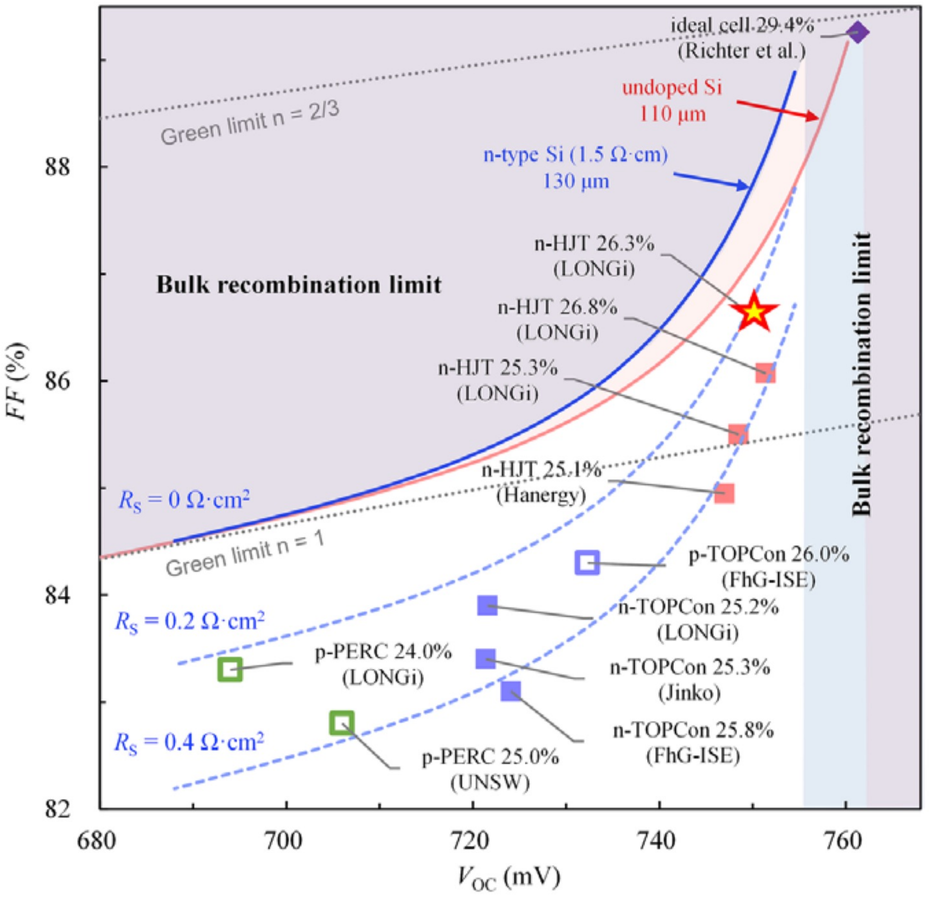
Hao Lin[1,2,4], Miao Yang[1,4], Xiaoning Ru[1,4], Genshun Wang[1,2], Shi Yin[1], Fuguo Peng[1], Chengjian Hong[1], Minghao Qu[1], Junxiong Lu[1], Liang Fang[1], Can Han[2,3], Paul Procel[3], Olindo Isabella[3], Pingqi Gao[2], Zhenguo Li[1] & Xixiang Xu[1]

Received: 21 December 2022

Accepted: 24 March 2023

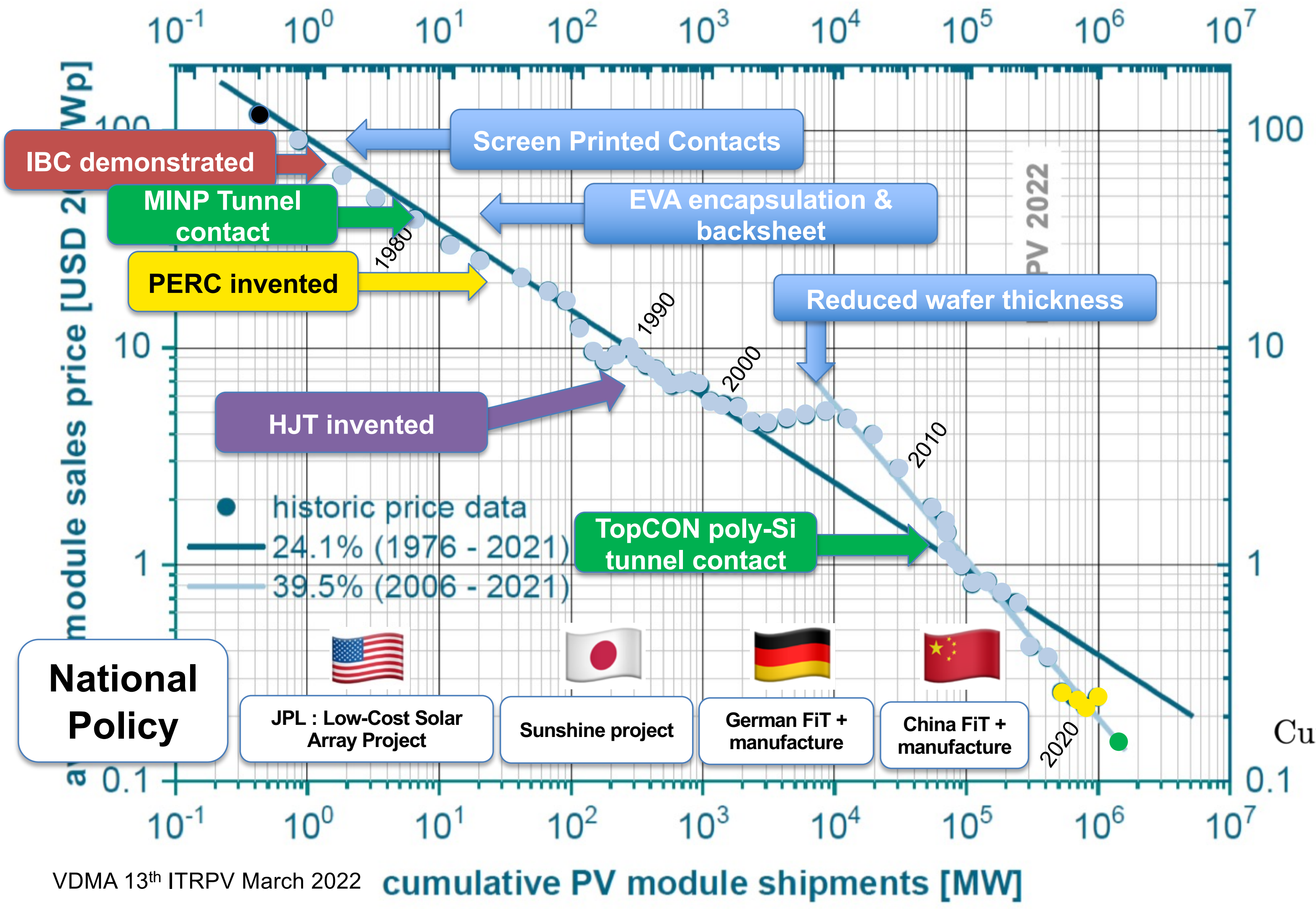






Lin, Hao, Wang, Genshun, Su, Qiao, Han, Can, Xue, Chaowei, Yin, Shi, Fang, Liang, Xu, Xixiang, & Gao, Pingqi. 'Unveiling the mechanism of attaining high fill factor in silicon solar cells'. Progress in Photovoltaics: Research and Applications, (2024) doi: 10.1002/pip.3775

Silicon PV Technology :



IBC demonstrated

MINP Tunnel contact

PERC invented

Screen Printed Contacts

EVA encapsulation & backsheet

Reduced wafer thickness

HJT invented

TopCON poly-Si tunnel contact

National Policy

JPL : Low-Cost Solar Array Project

Sunshine project

German FiT + manufacture

China FiT + manufacture

VDMA 13th ITRPV March 2022

Black cell

Al-BSF

IBC

TopCON

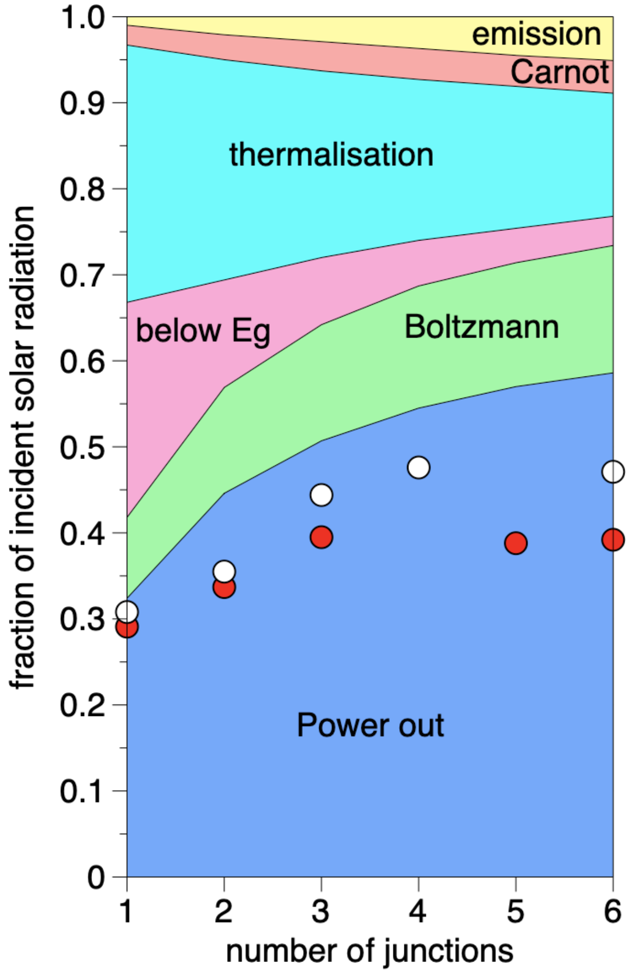
PERC

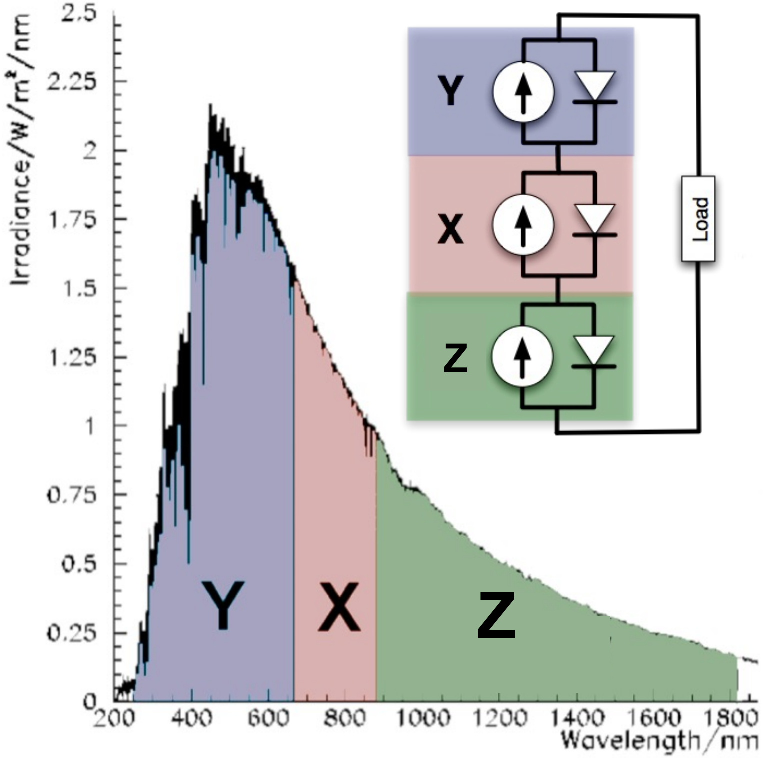
HJT

$$\text{Cumulative market sales} = \int_{x_0}^{x_1} y\,dy$$

M.A. Green. 'Photovoltaic technology and visions for the future'. *Progress in Energy*, *1*(2019) 013001
G.F. Nemet, How Solar Energy Became Cheap, Routledge 2019

Multi-Junction Solar Cells : The Standard Path to High Efficiency





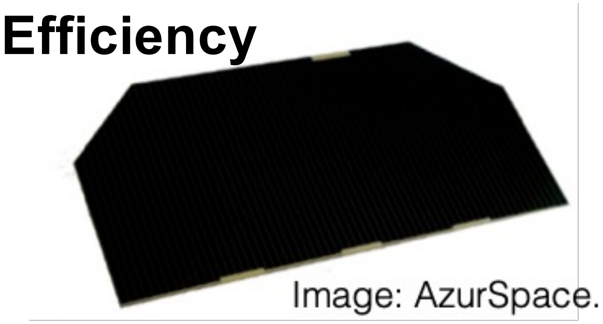
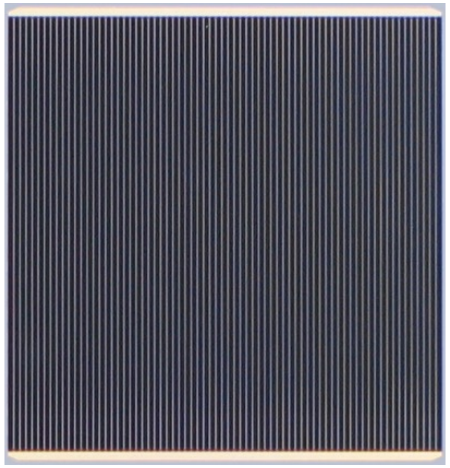


Image: AzurSpace.

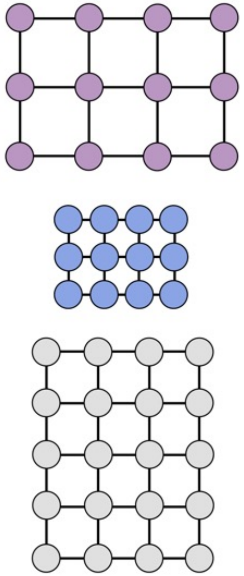
~32% 3J Space Solar Cell AM0

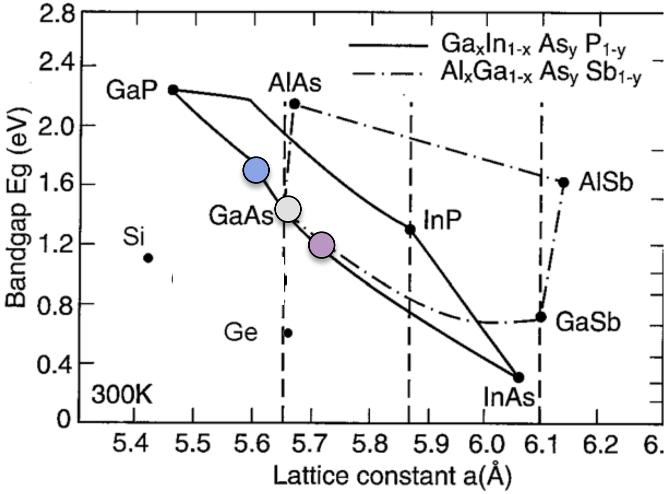


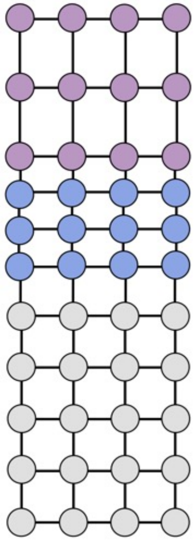
~40% 3J Concentrator Solar Cell AM1.5D

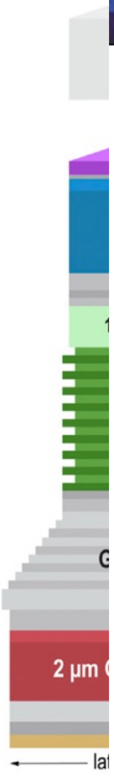
L. Hirst & N.J.Ekins-Daukes, Progress in Photovoltaics, (2011) 19: p286

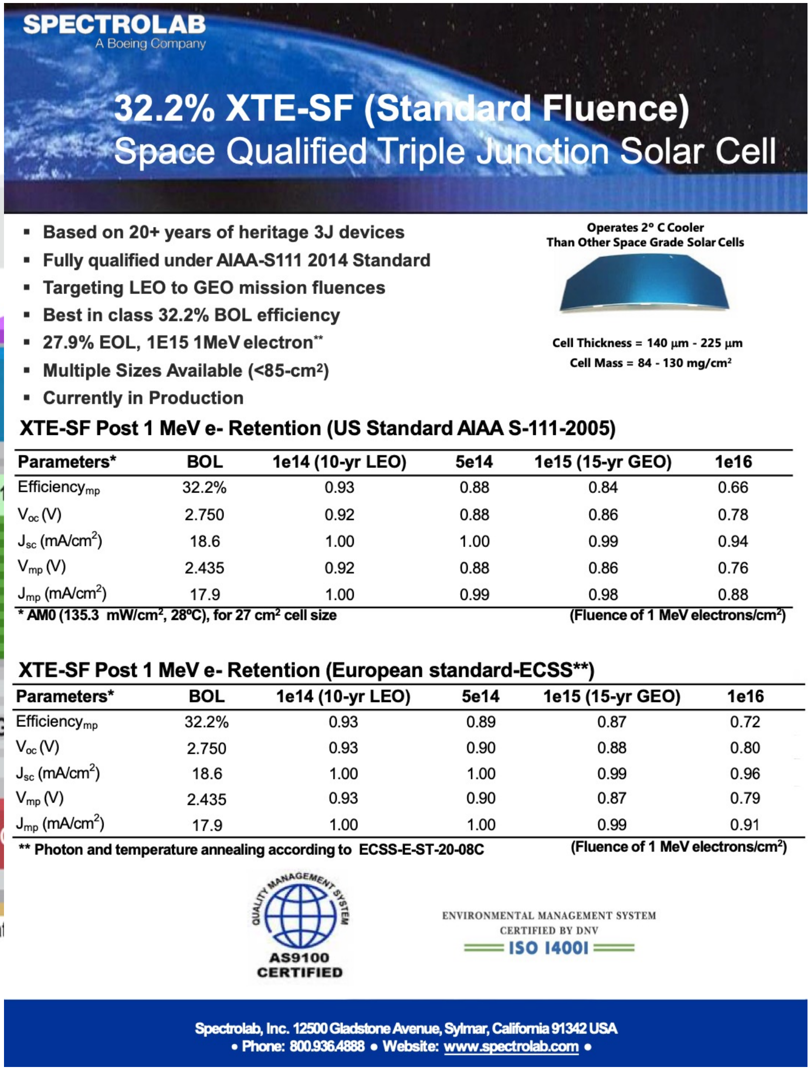
Strain-Balance Quantum Well Solar Cell











SPECTROLAB
A Boeing Company

32.2% XTE-SF (Standard Fluence)
Space Qualified Triple Junction Solar Cell

- **Based on 20+ years of heritage 3J devices**
- **Fully qualified under AIAA-S111 2014 Standard**
- **Targeting LEO to GEO mission fluences**
- **Best in class 32.2% BOL efficiency**
- **27.9% EOL, 1E15 1MeV electron****
- **Multiple Sizes Available (<85-cm²)**
- **Currently in Production**

Operates 2° C Cooler
Than Other Space Grade Solar Cells

Cell Thickness = 140 µm - 225 µm
Cell Mass = 84 - 130 mg/cm²

XTE-SF Post 1 MeV e- Retention (US Standard AIAA S-111-2005)

Parameters*	BOL	1e14 (10-yr LEO)	5e14	1e15 (15-yr GEO)	1e16
$Efficiency_{mp}$	32.2%	0.93	0.88	0.84	0.66
V_{oc} (V)	2.750	0.92	0.88	0.86	0.78
J_{sc} (mA/cm^2)	18.6	1.00	1.00	0.99	0.94
V_{mp} (V)	2.435	0.92	0.88	0.86	0.76
J_{mp} (mA/cm^2)	17.9	1.00	0.99	0.98	0.88

*** AM0 (135.3 mW/cm², 28°C), for 27 cm² cell size** **(Fluence of 1 MeV electrons/cm²)**

XTE-SF Post 1 MeV e- Retention (European standard-ECSS)**

Parameters*	BOL	1e14 (10-yr LEO)	5e14	1e15 (15-yr GEO)	1e16
$Efficiency_{mp}$	32.2%	0.93	0.89	0.87	0.72
V_{oc} (V)	2.750	0.93	0.90	0.88	0.80
J_{sc} (mA/cm^2)	18.6	1.00	1.00	0.99	0.96
V_{mp} (V)	2.435	0.93	0.90	0.87	0.79
J_{mp} (mA/cm^2)	17.9	1.00	1.00	0.99	0.91

**** Photon and temperature annealing according to ECSS-E-ST-20-08C** **(Fluence of 1 MeV electrons/cm²)**

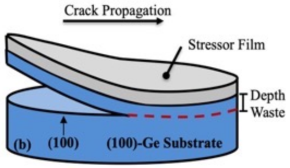
QUALITY MANAGEMENT SYSTEM
AS9100
CERTIFIED

ENVIRONMENTAL MANAGEMENT SYSTEM
CERTIFIED BY DNV
ISO 14001

Spectrolab, Inc. 12500 Gladstone Avenue, Sylmar, California 91342 USA
• Phone: 800.936.4888 • Website: www.spectrolab.com •

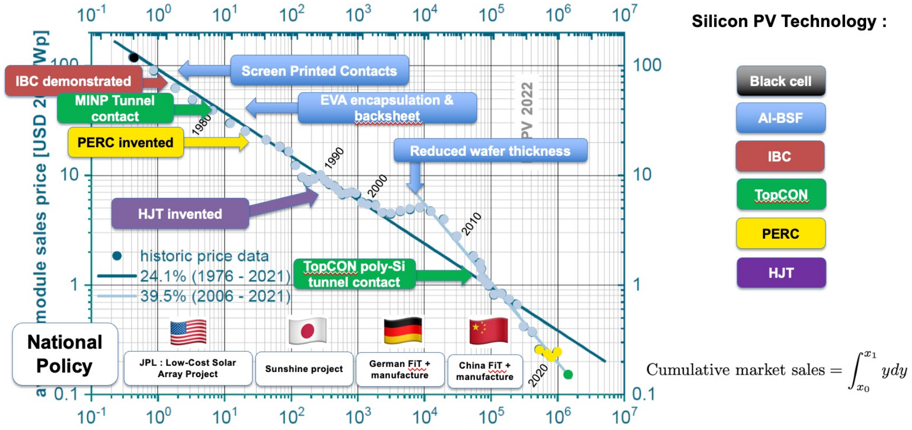
Ekins-Daukes, N. J., et al., (**1999**). Strain-balanced GaAsP/InGaAs quantum well solar cells. Appl.Phys.Lett. 75(26), 4195-4197.

France,



Observations from multi-junction PV manufacturing :

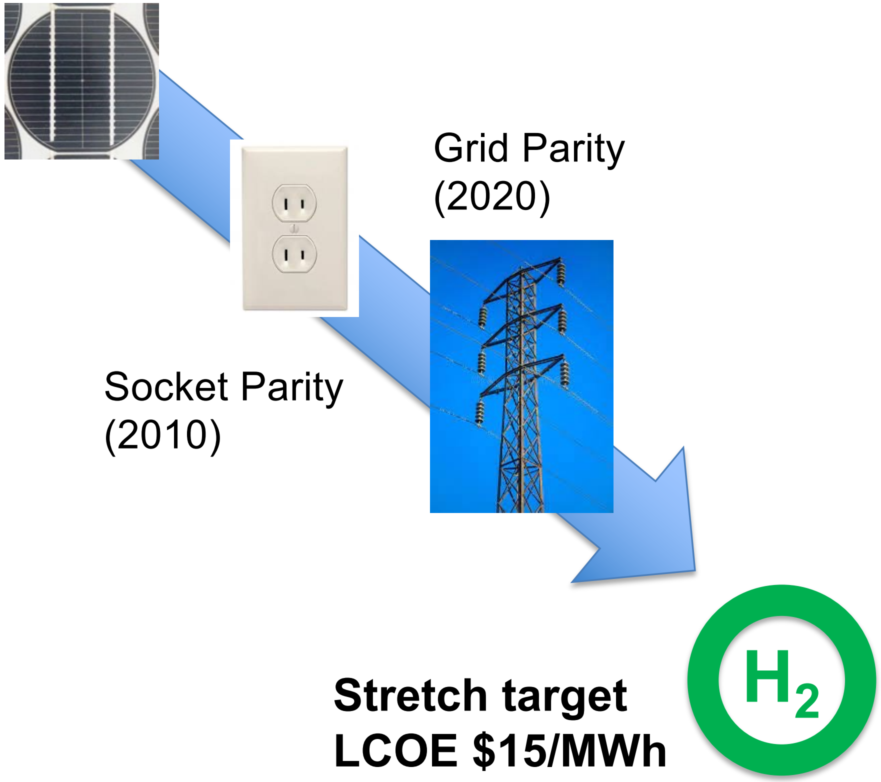
1. Structural complexity in tandem solar cells is often easier to manage than chemical complexity
2. III-V PV is **“expensive” for non-essential reasons** :
   - Highly specialized space PV market where efficiency and reliability are more important than cost
   - Tiny manufacturing volumes. Larger markets may provide a pathway for PV >30% at ~$5/Wp .
   - Inactive substrate that only serves only as a crystal template for epitaxy.



$$\text{Cumulative market sales} = \int_{x_0}^{x_1} y\,dy$$

VDMA 13th ITRPV March 2022

Australian Government Objective : Ultra Low Cost Solar PV Research and Development



Space PV (1958)

Grid Parity (2020)

Socket Parity (2010)

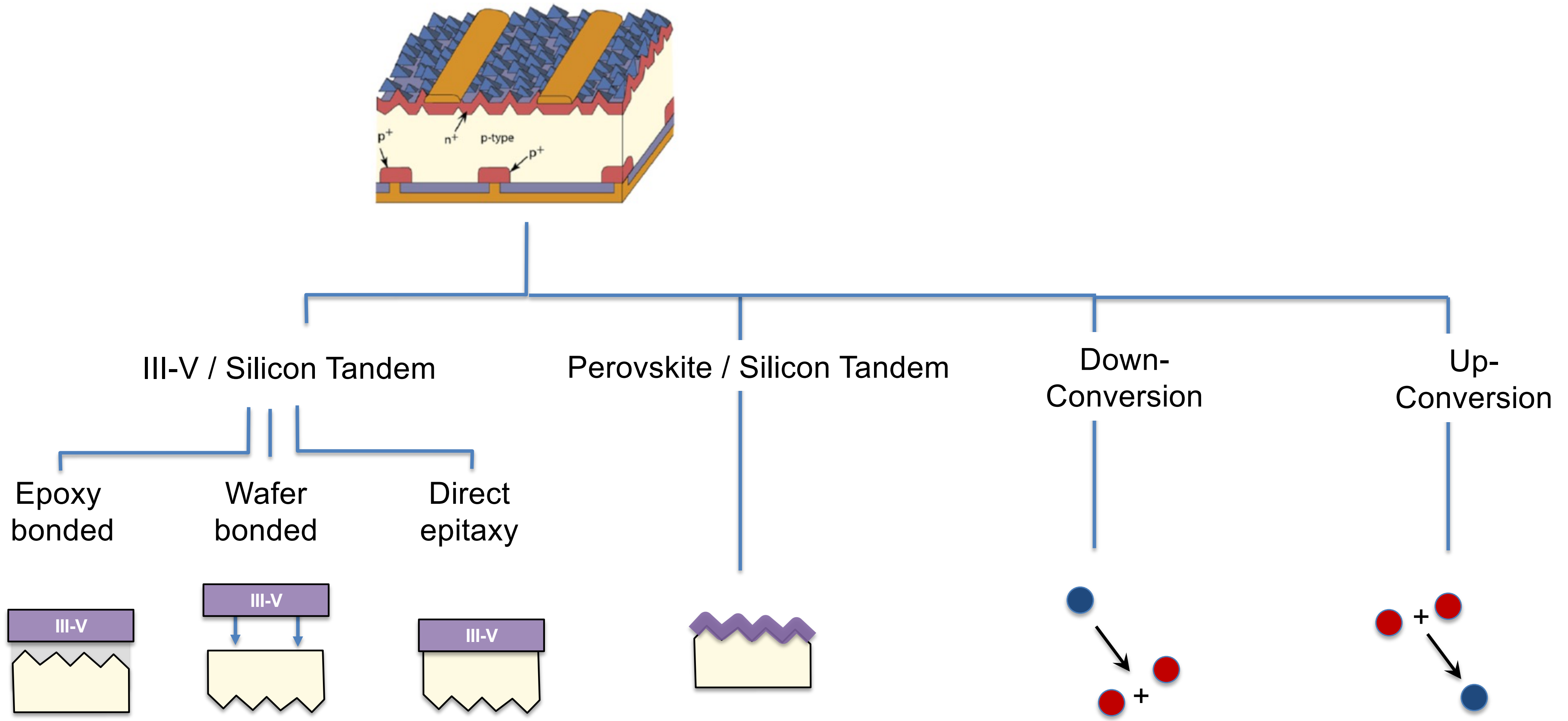
Stretch target LCOE $15/MWh

30 : 30 : 30 Strategy

- **> 30% Module Efficiency**
- **30¢ / Wp system capacity cost**
- **Achieved by 2030**

Australian Government
Australian Renewable Energy Agency

Routes to improve Silicon PV Efficiency:



III-V / Silicon Tandem

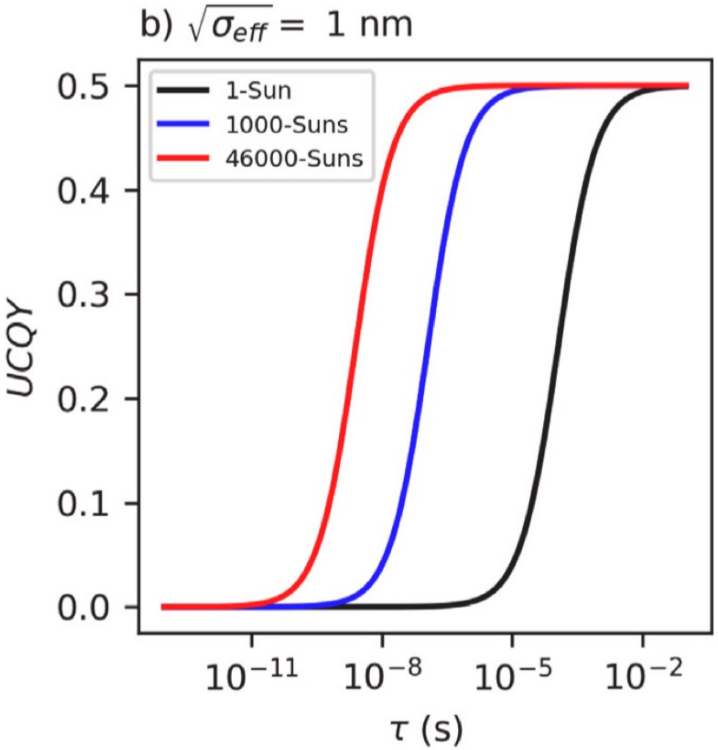
- Epoxy bonded
- Wafer bonded
- Direct epitaxy

Perovskite / Silicon Tandem

Down-Conversion

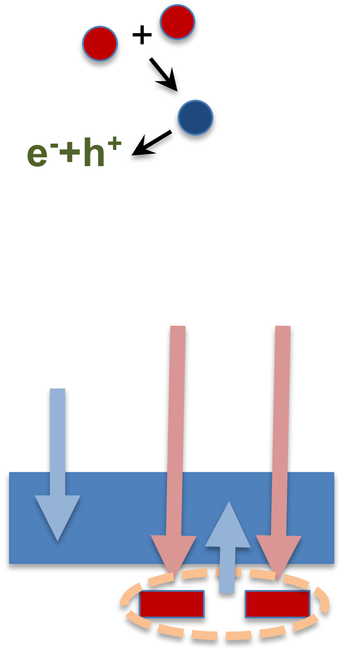
Up-Conversion

Tandem



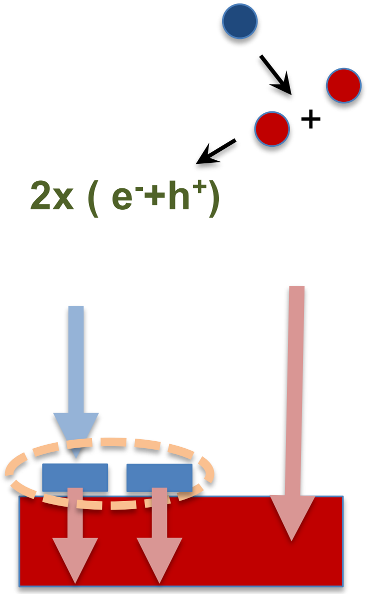
sub-cell needs to be matched

Up-Conversion



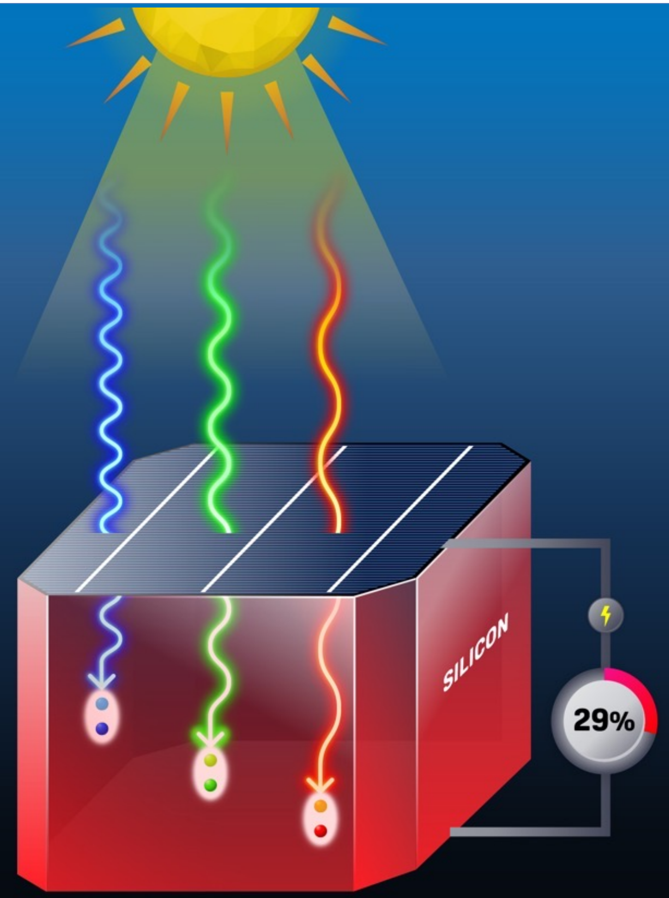
Simultaneous absorption of light in two interacting absorbers.

Down-Conversion

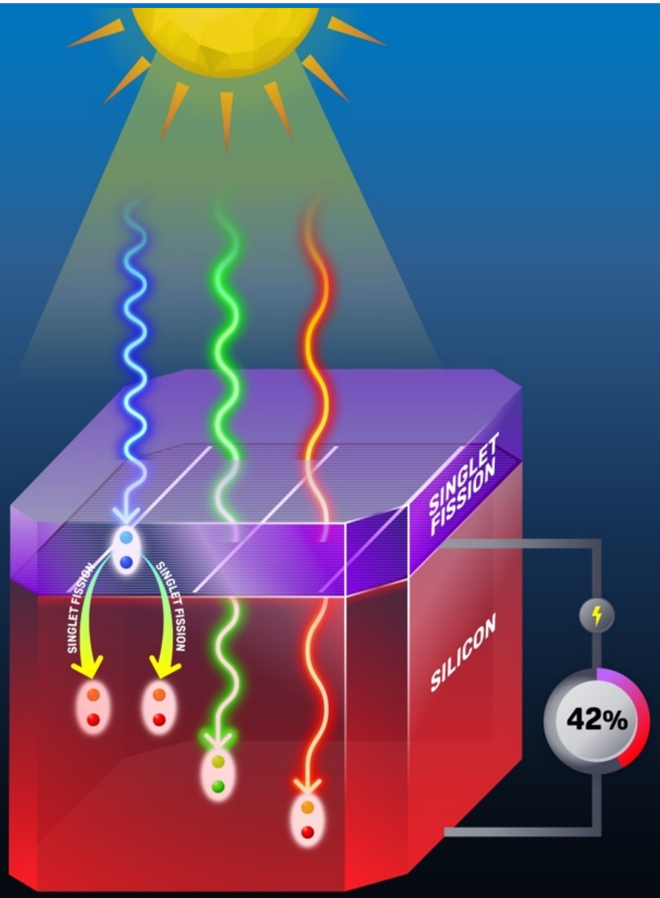


Interaction between one excited absorber and a neighbour.

Sharma, Abhinav, Pusch, Andreas, Nielsen, Michael P, Romer, Udo, Tayebjee, Murad J Y, Rougieux, Fiacre, & Ekins-Daukes, Nicholas J. ’Constraints imposed by the sparse solar photon flux on upconversion and hot carrier solar cells’. *Solar Energy*, *237*(2022) 44



Conventional Silicon PV



Molecular Singlet Fission on Silicon

Australian Government
Australian Renewable Energy Agency

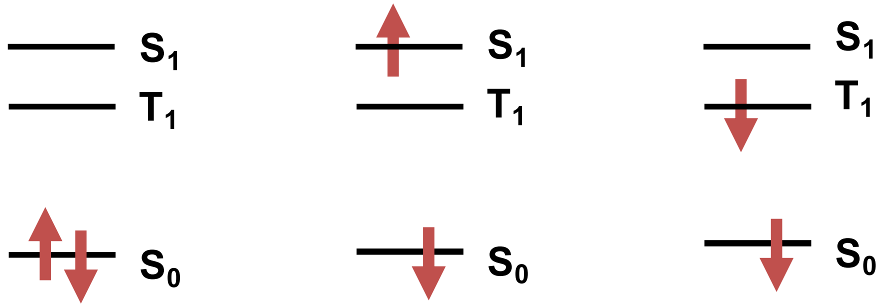
ΩSILICON

www.omegasilicon.solar

UNSW SYDNEY

What is Molecular Singlet Fission ?

All molecules have singlet & triplet states; different electron spin configurations:



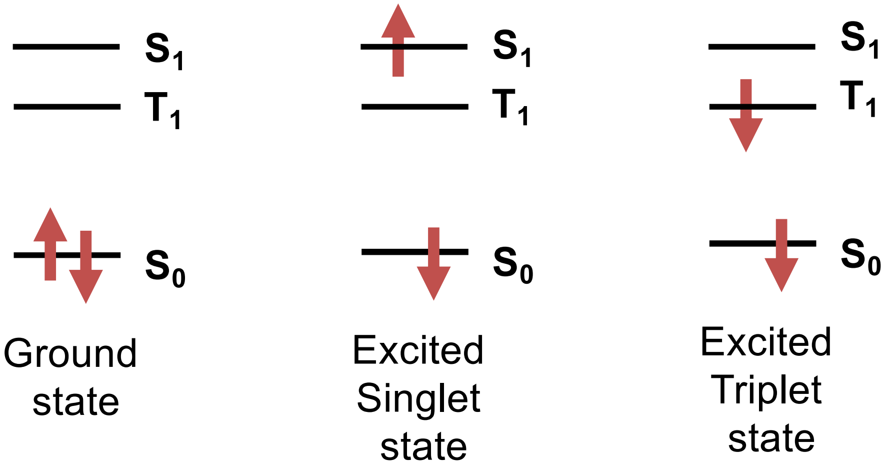
Ground state

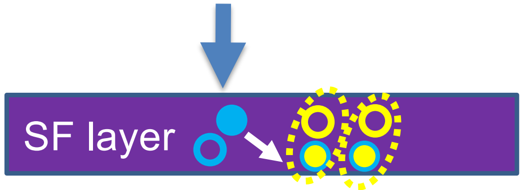
Excited Singlet state

Excited Triplet state

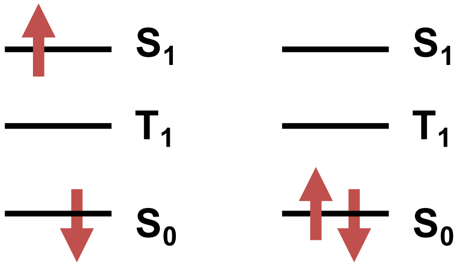
What is Molecular Singlet Fission ?

All molecules have singlet & triplet states; different electron spin configurations:

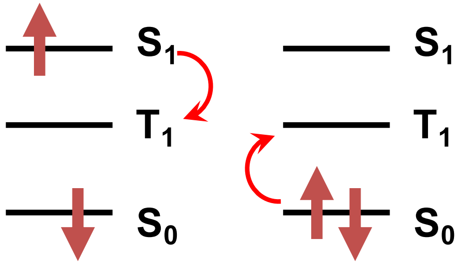




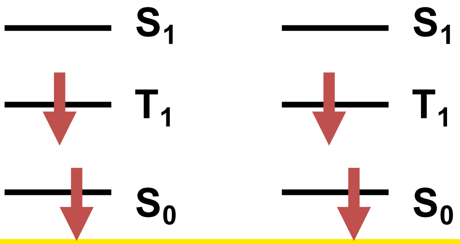
① Short-wavelength light excites one molecule into the singlet excited state.



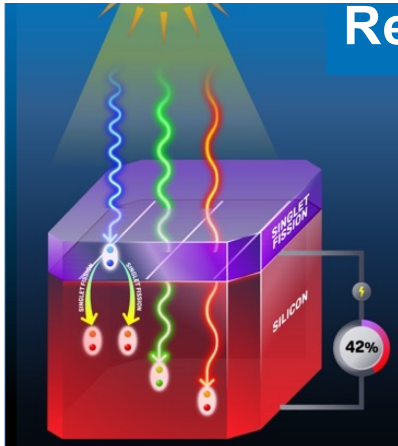
② Half the S_1 energy is transferred to a neighbouring molecule. (Spin is conserved, electrons on both molecules change spin)



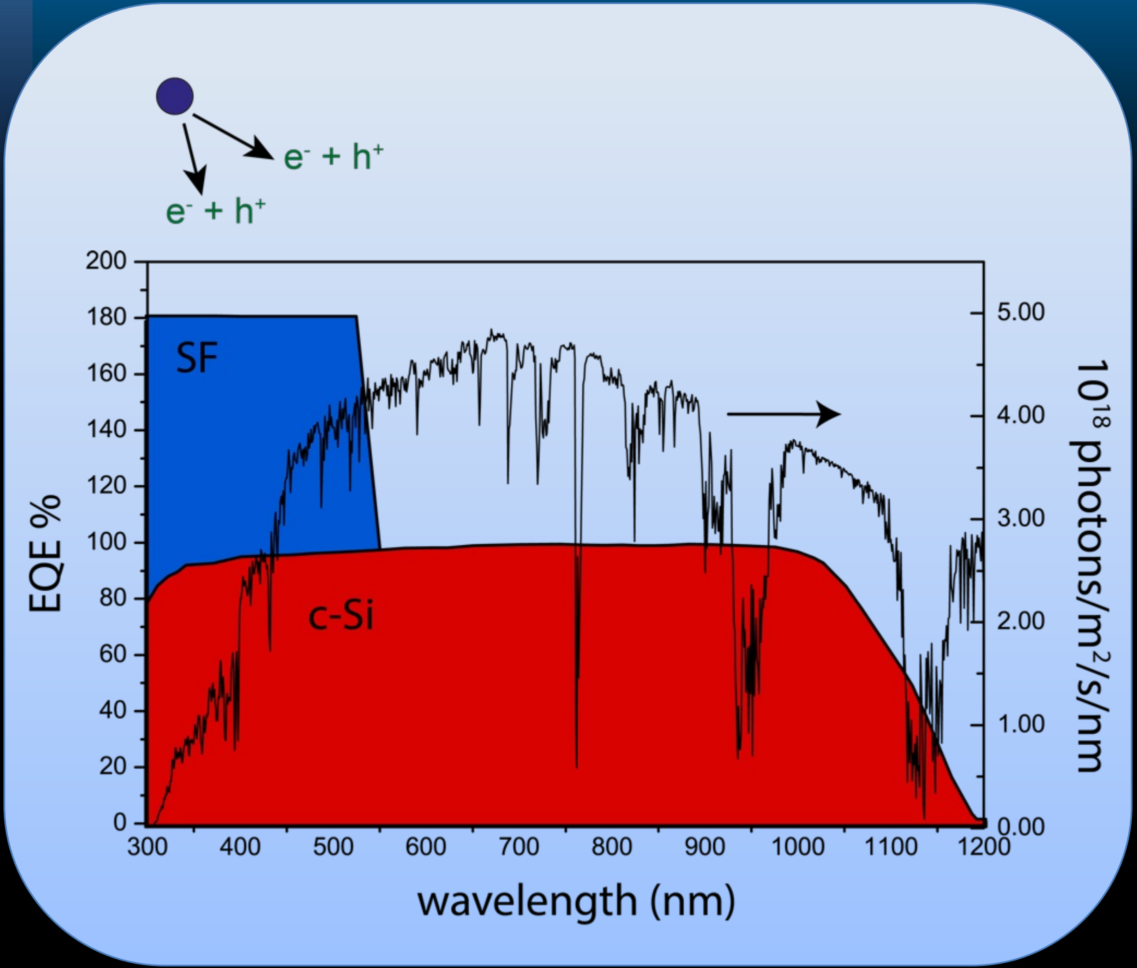
③ Both molecules enter their excited triplet state.



Requirements for EQE >100% results from singlet fission:



SINGLET FISSION ON SILICON PV



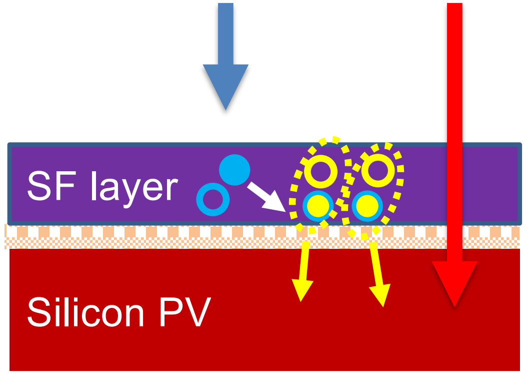
Molecular layer that absorbs short wavelength light

Two molecules interact to undergo singlet fission producing two triplet excitons (bound e-h pairs)

🟧 e-h pairs are transferred into silicon

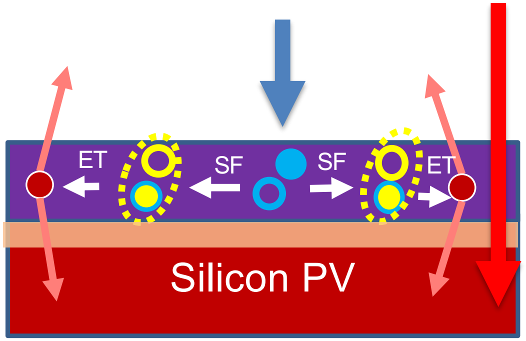
Two technological pathways

Direct Energy Transfer



Passivating Interlayer (allows triplet energy Transfer)

Radiative Optical Transfer

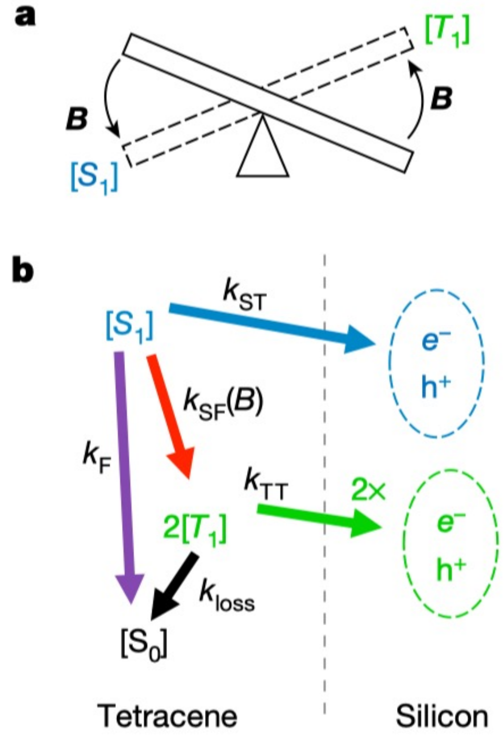


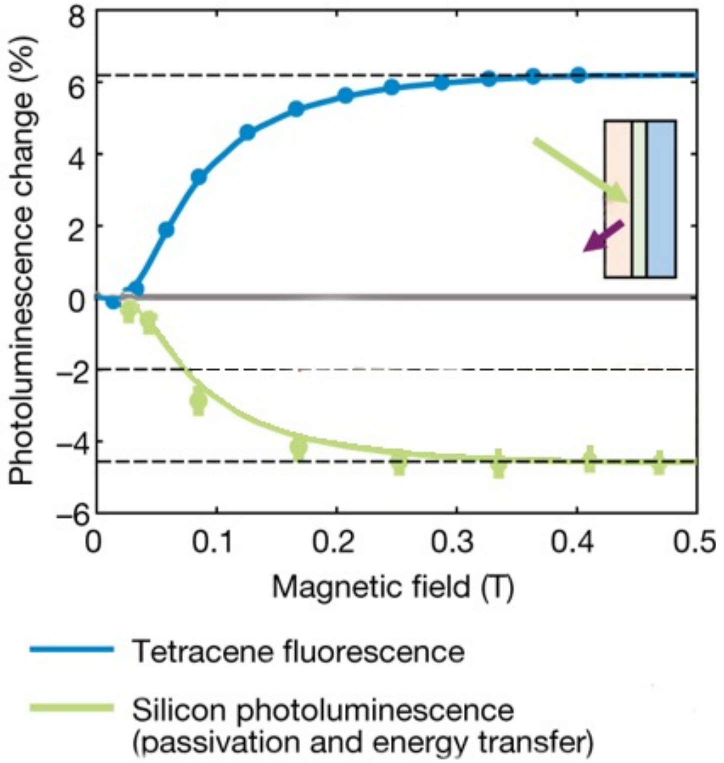
Passivating layer

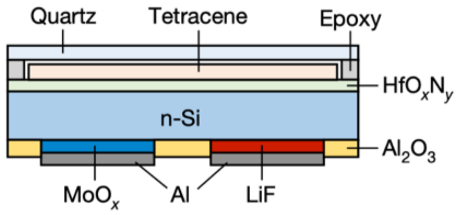
- ✓ **Highest efficiency potential (>40% limit)**
- ✓ **Well suited to IBC architecture**
- **Requires :**
  - **Dedicated singlet fission molecular layer**
  - **Passivating exciton transport interlayer**
    - **HfNOx demonstrated**
    - **New interlayer materials required**

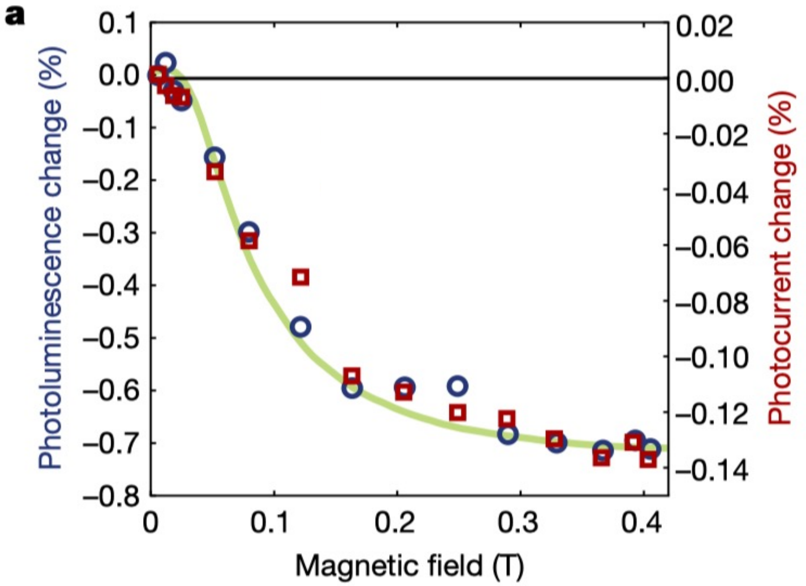
- ✓ **Lower efficiency potential (>30%)**
- **Requires highly emissive lumiphores**
- ✓ **Surface passivation and cell structure unchanged**
- ✓ **Fast route for efficiency gain**
- ✓ **Compatible with luminescent down shifting films and heterojunction cells**

Direct Energy Transfer : State of the art
as published to date









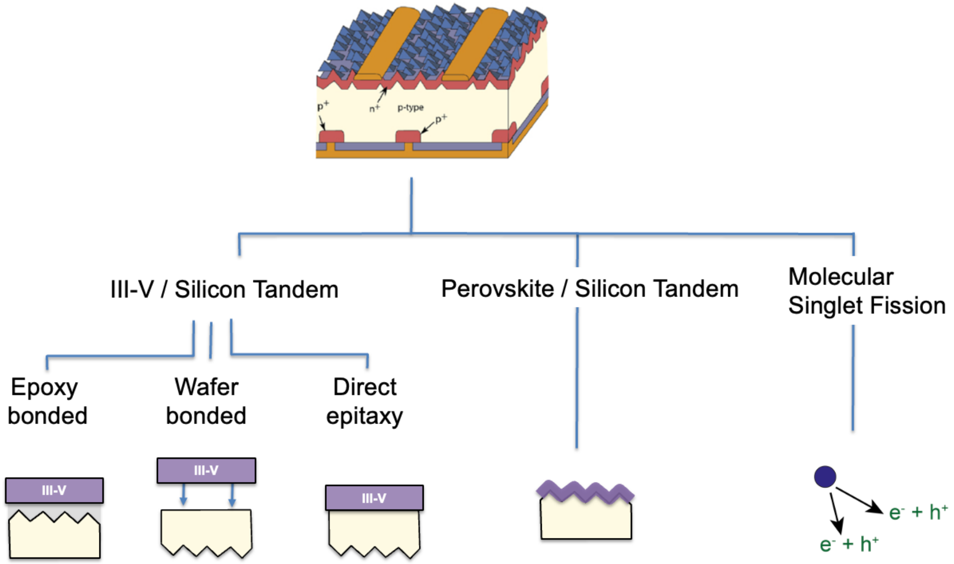
Selective contact MoOx/LiF IBC architecture :
Um, Han-Don, et al., 'Dopant-Free All-Back-Contact Si Nanohole Solar Cells Using MoOx and LiF Films'. Nano Letters, 16(2) (2016) 981

Einzinger, M.; Wu, T.; Kompalla, J. F.; Smith, H. L.; Perkinson, C. F.; Nienhaus, L.; Wieghold, S.; Congreve, D. N.; Kahn, A.; Bawendi, M. G.; Baldo, M. A. Nature 2019, 571 (7763), 90–94.

Observations for Silicon Multiple Threshold

1. High-performance research lab PV results achieved for multiple silicon tandem technologies:
   1. III-V / Silicon Tandem (36.1% wafer bonded)
   2. Silicon Perovskite (33.9%)
   3. Molecular Singlet Fission (TBC)

2. Which technology is the pathway for large area, low-cost, mass manufacture with long term stability ?



III-V / Silicon Tandem

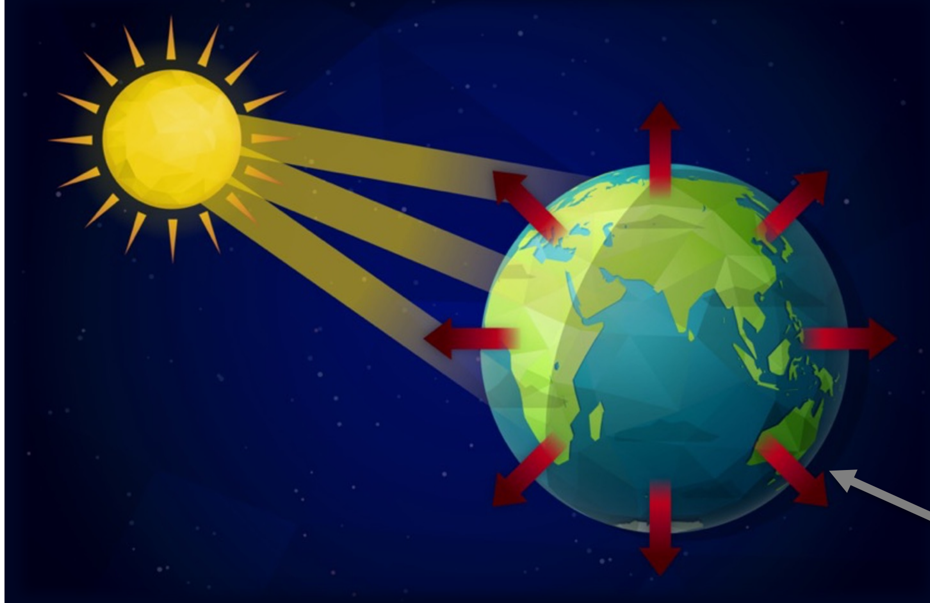
Epoxy bonded

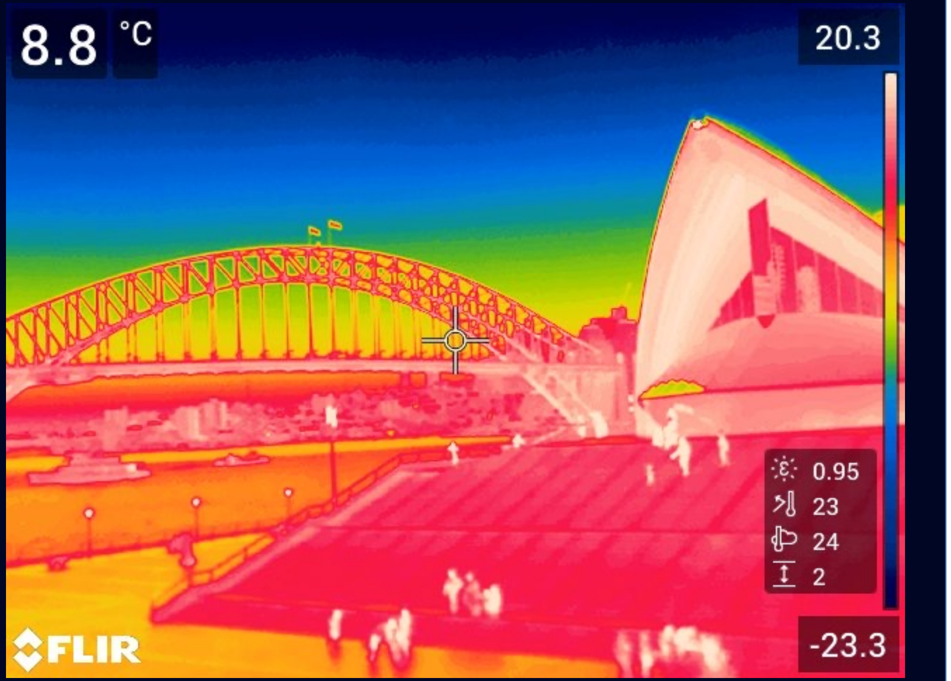
Wafer bonded

Direct epitaxy

Perovskite / Silicon Tandem

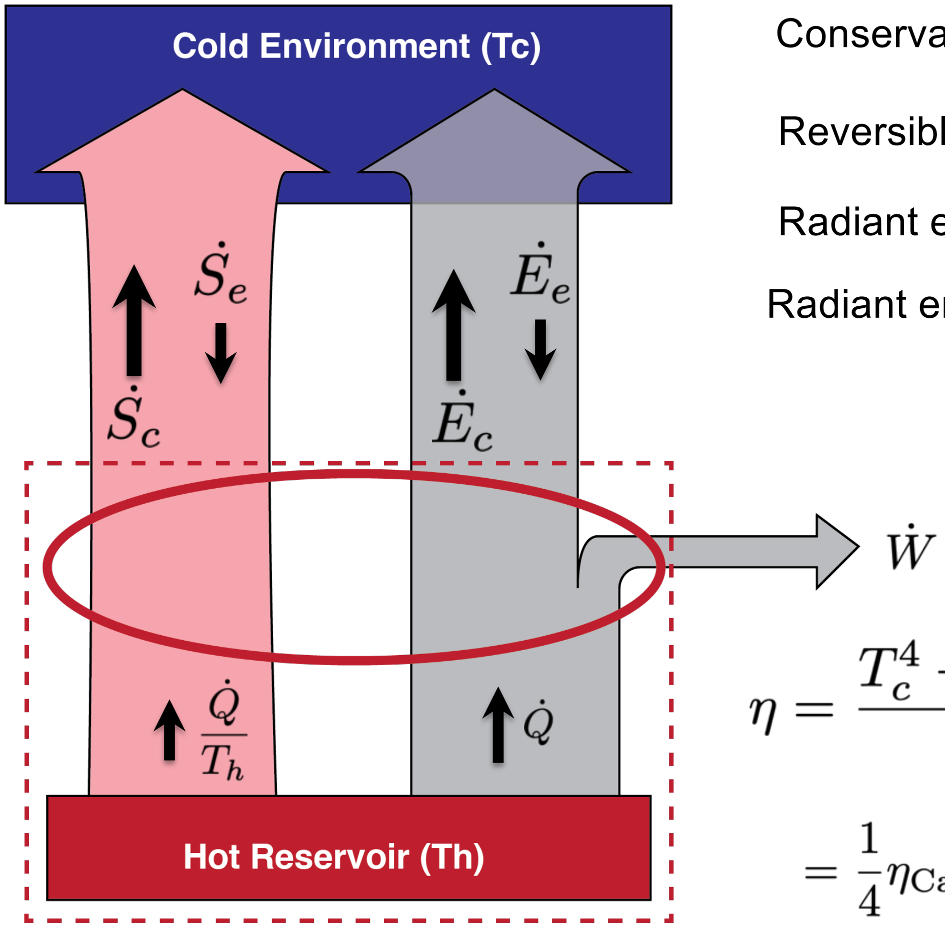
Molecular Singlet Fission





Sydney Opera House, thermal image (9pm)

Electrical Power from Radiative Processes : Thermoradiative Conversion



Conservation of Energy: $\dot{Q} + \dot{E}_e = \dot{W} + \dot{E}_c$

Reversible operation: $\dot{S}_c = \dot{S}_e + \frac{\dot{Q}}{T_h}$

Radiant energy flux density: $\dot{E} = \sigma T^4$

Radiant entropy flux density: $\dot{S} = \frac{4}{3}\sigma T^3$

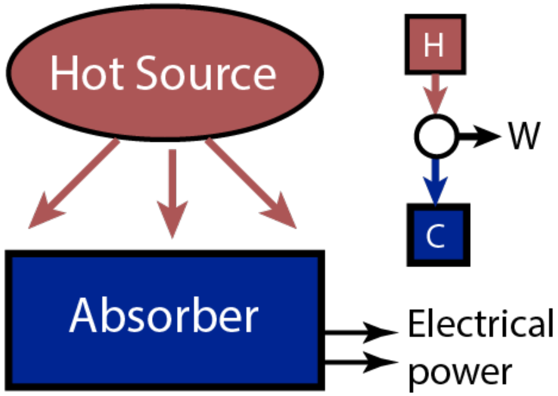
$$\eta = \frac{\dot{W}}{\dot{Q}}$$

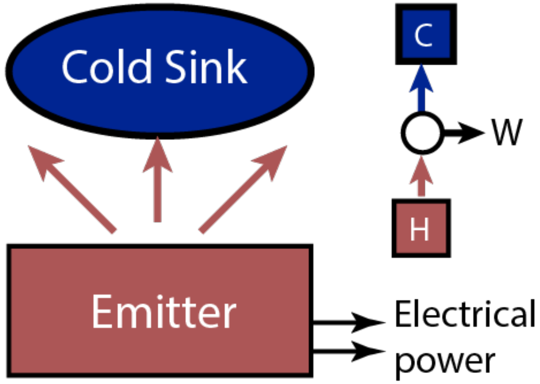
$$\eta = \frac{T_c^4 + (1/3)T_h^4 - (4/3)T_h T_c^3}{(4/3)\left(T_h^4 - T_h T_c^3\right)}$$

$$= \frac{1}{4}\eta_{\text{Carnot}} \frac{1 + 2\left(T_c/T_h\right) + 3\left(T_c/T_h\right)^2}{1 + T_c/T_h + \left(T_c/T_h\right)^2}$$

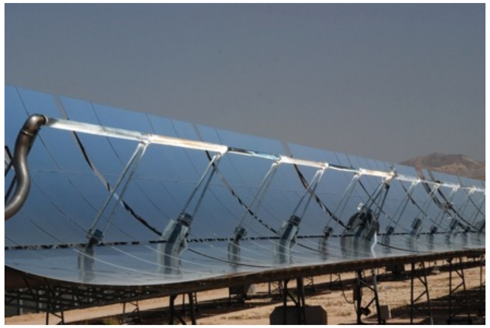
A.Pusch, J.M.Gordon, A.Mellor, J.J.Krich, & N.J.Ekins-Daukes, *Physical Review Applied* **12**, 064018 (2019).

Electrical Power from Radiative Processes





Thermal Solar Power

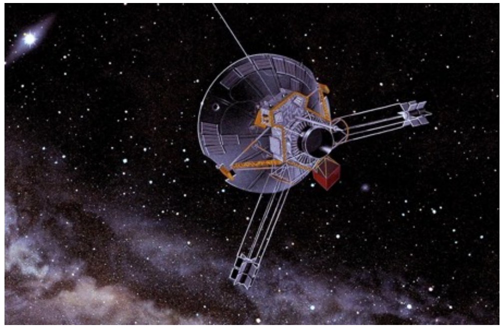


Steam Rankine cycle

Quantum Solar Power

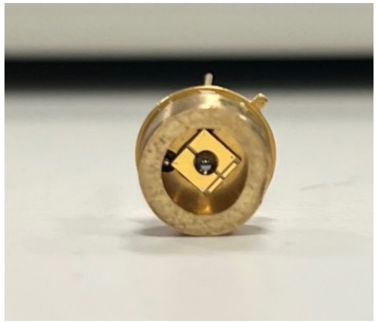
Semiconductor Diode

Thermoradiative Power



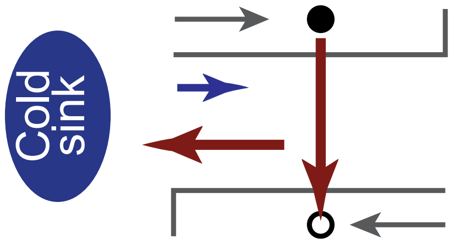
Radioisotope Thermoelectric Generator

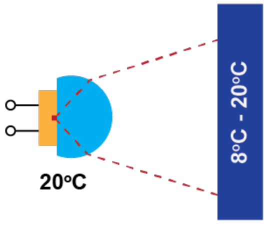
Quantum Thermoradiative Power



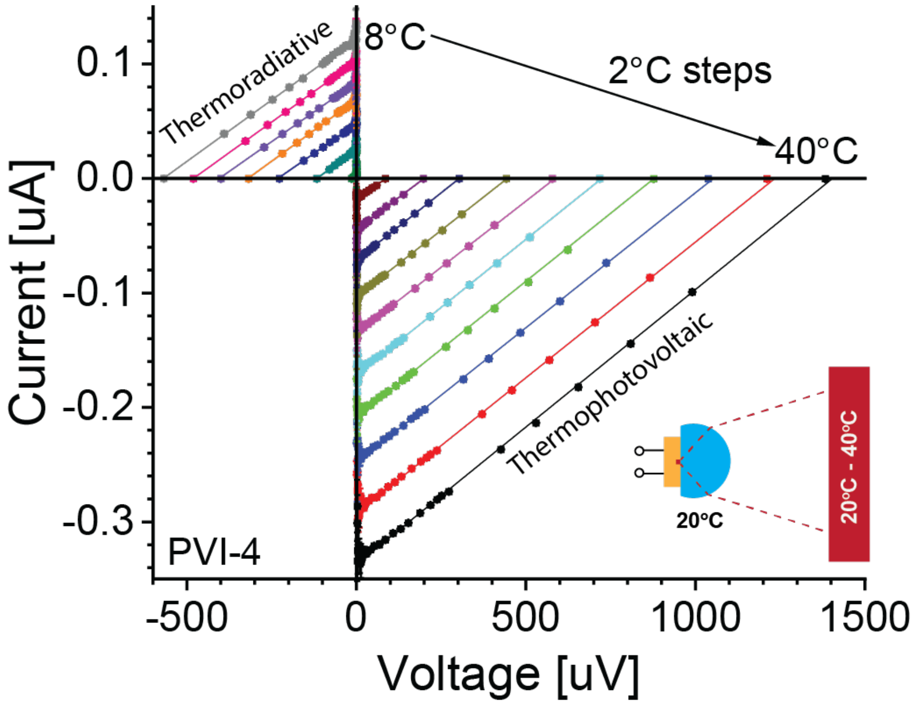
Thermoradiative Diode

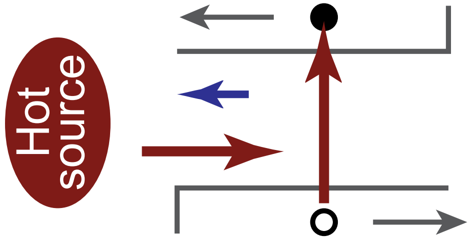
Thermoradiative and Thermophotovoltaic Power





HgCdTe Photodiode,
Eg=0.25eV, T= 20.5°C

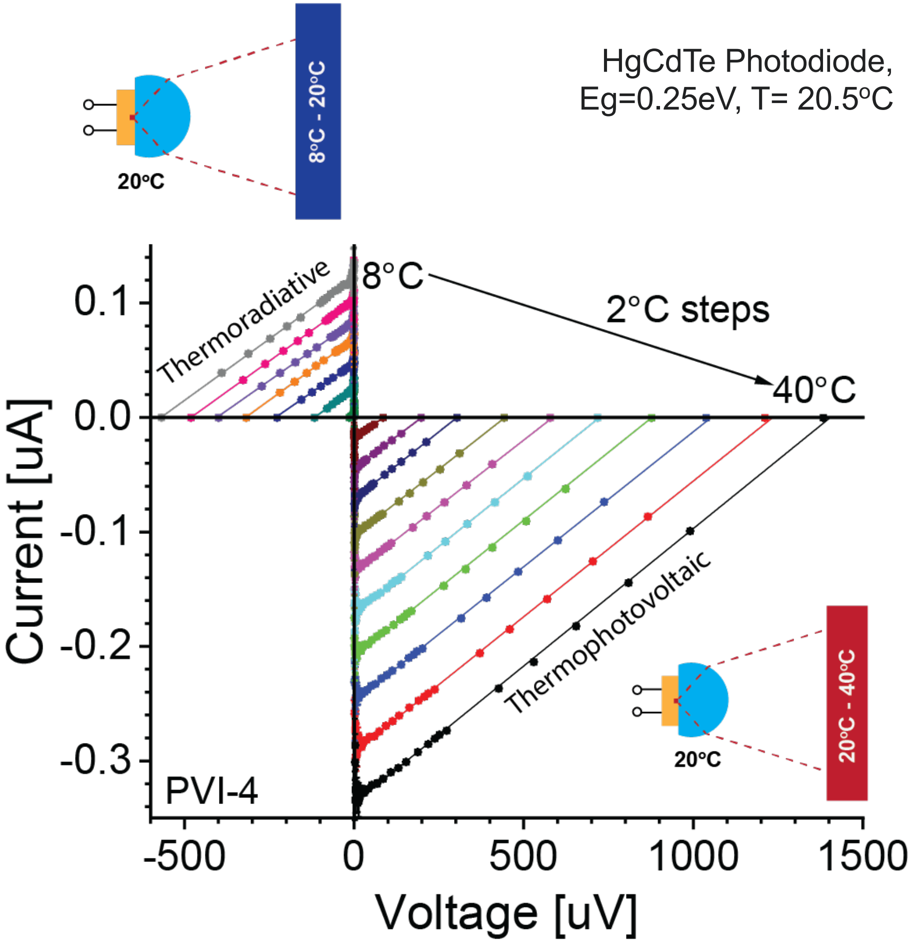


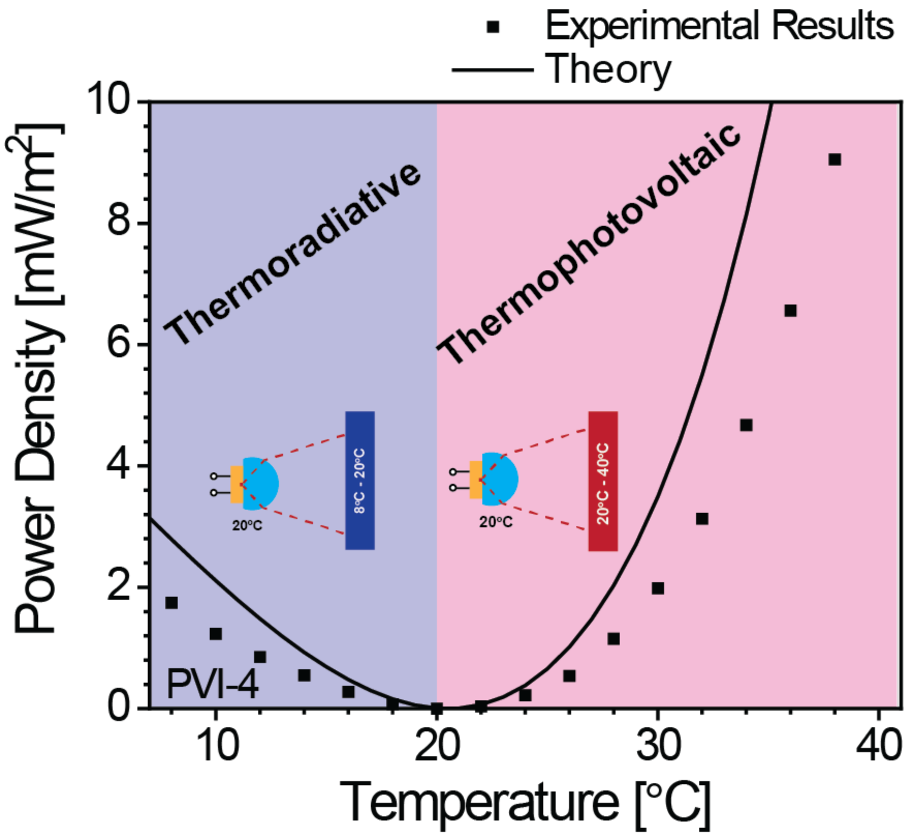


Nielsen, M. P., Pusch, A., Sazzad, M. H., Pearce, P. M., Reece, P. J., & Ekins-Daukes, N. J. (2022). Thermoradiative Power Conversion from HgCdTe Photodiodes and Their Current–Voltage Characteristics. ACS Photonics, 9(5), 1535-1540.

Thermoradiative and Thermophotovoltaic Power

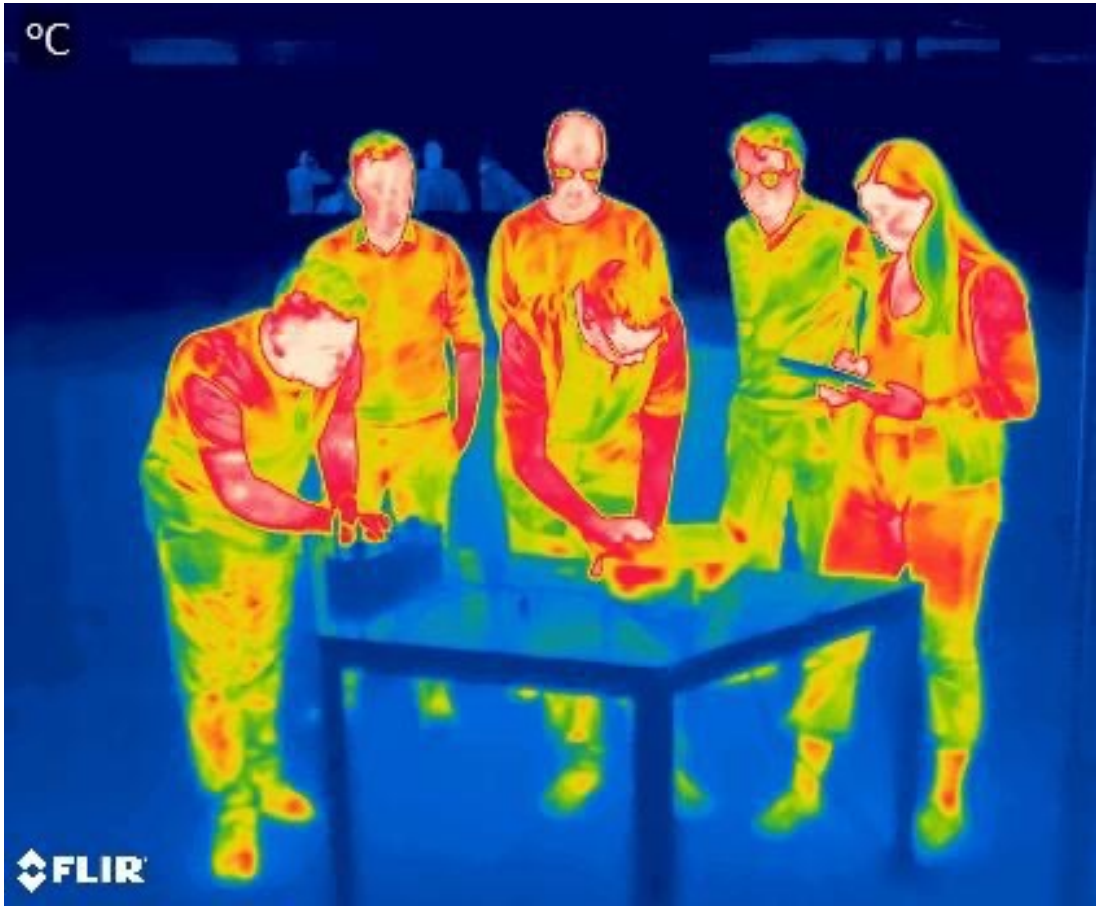
HgCdTe Photodiode,
Eg=0.25eV, T= 20.5°C



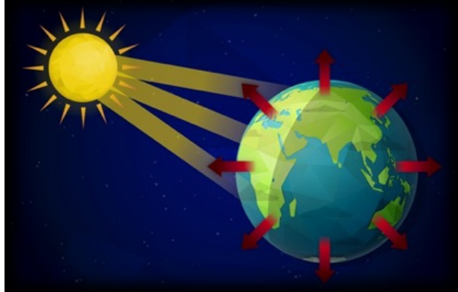


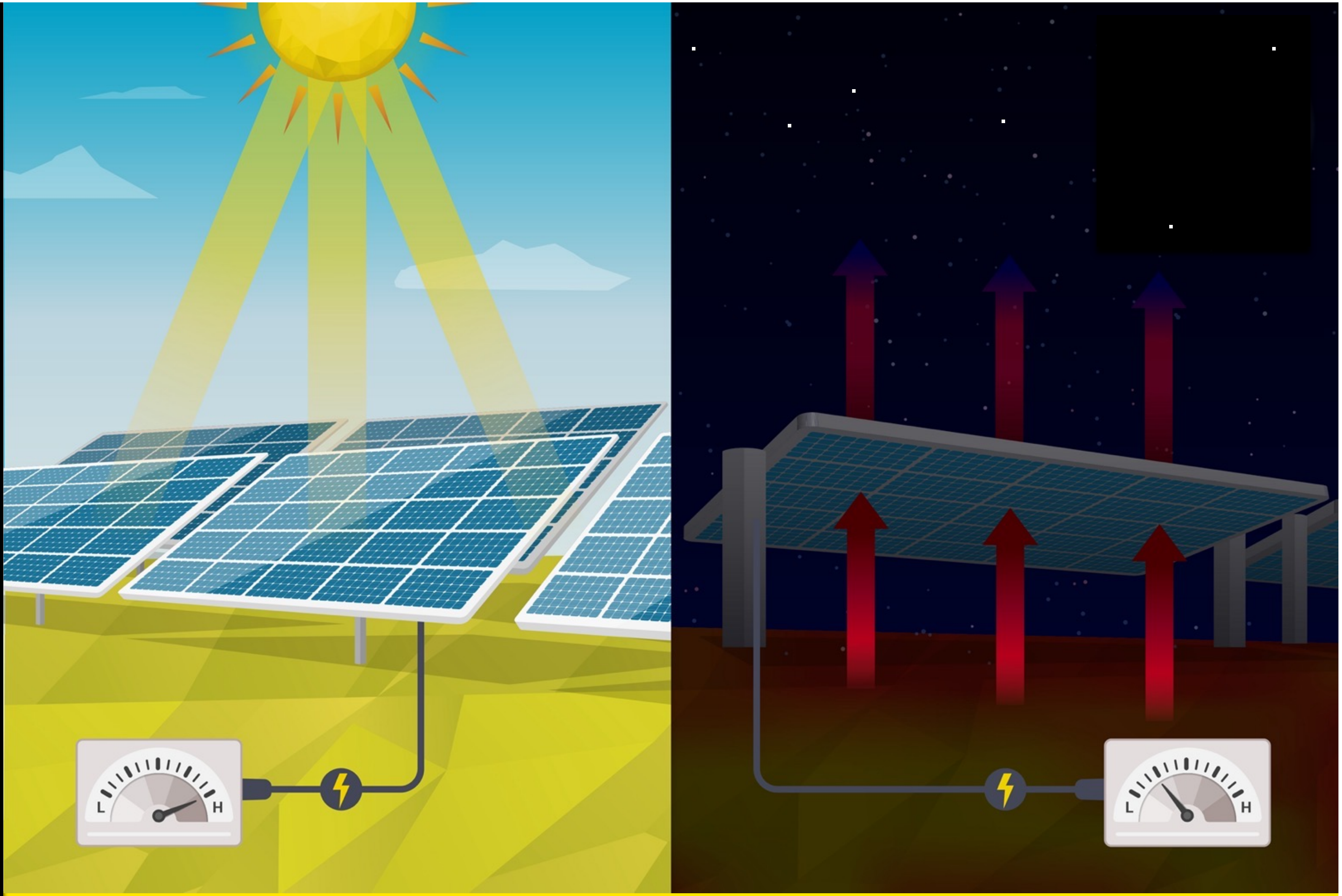
Nielsen, M. P., Pusch, A., Sazzad, M. H., Pearce, P. M., Reece, P. J., & Ekins-Daukes, N. J. (2022). Thermoradiative Power Conversion from HgCdTe Photodiodes and Their Current–Voltage Characteristics. ACS Photonics, 9(5), 1535-1540.

Thermoradiative power from body heat



Solar Energy Day & Night



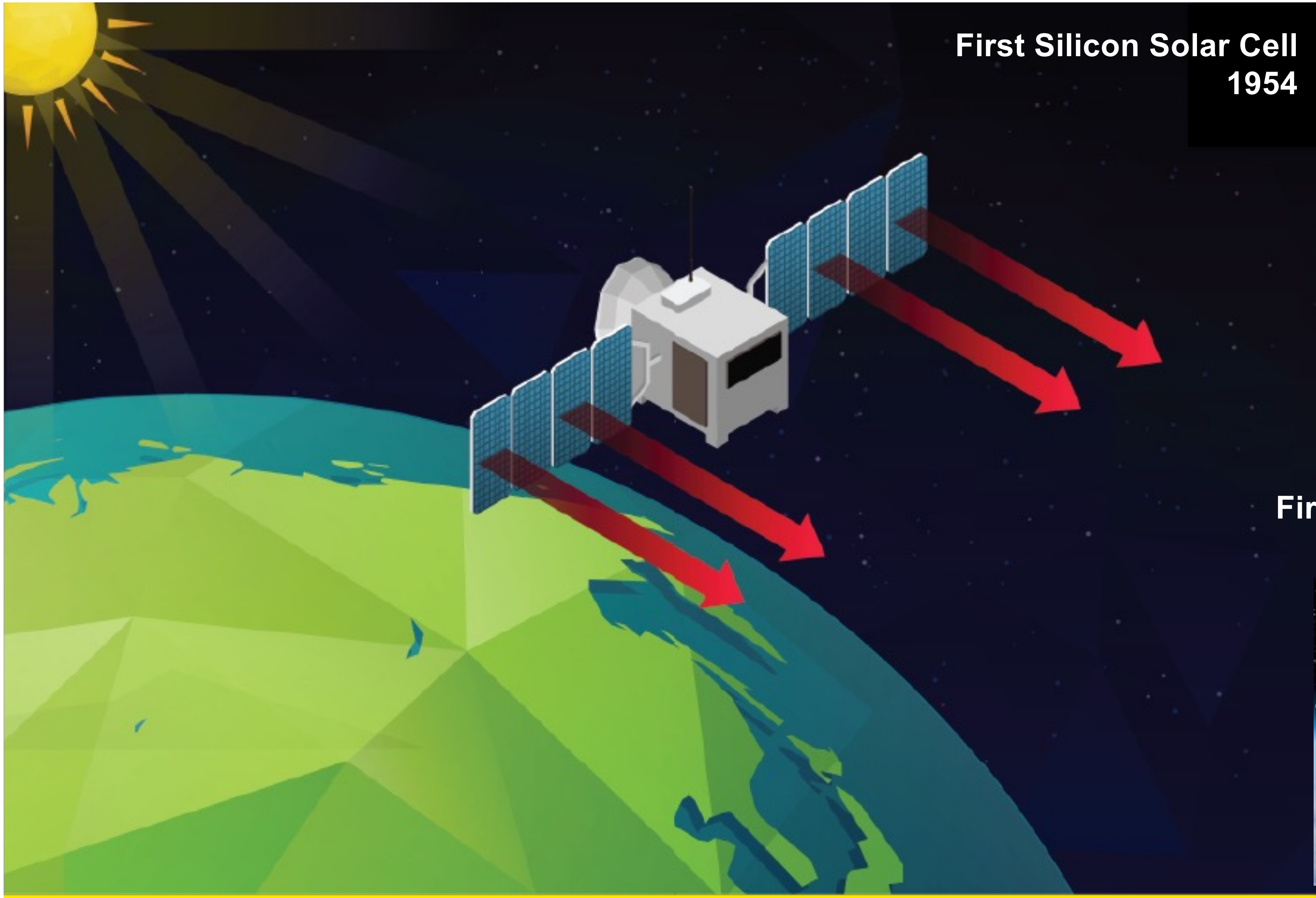


Electrical Power Density

Record Laboratory
(Thermodynamic limit)

Solar PV : 475W.m^{-2}
(868W.m^{-2})

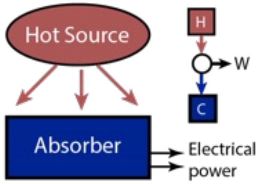
Thermoradiative : 5mW.m^{-2}
(10 W.m^{-2})

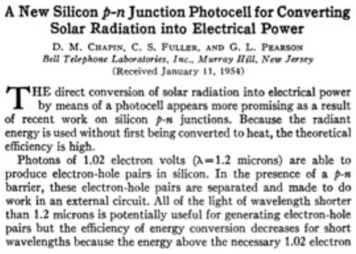


First Silicon Solar Cell
1954

First Solar Powered Satellite
Vanguard 1 1958

Conclusion:



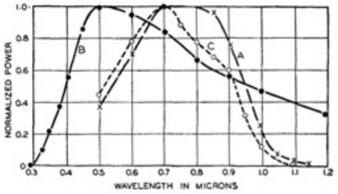


A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

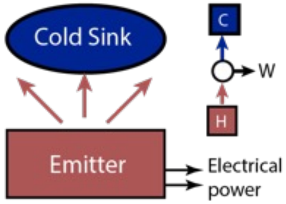
D. M. Chapin, C. S. Fuller, and G. L. Pearson
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received January 11, 1954)

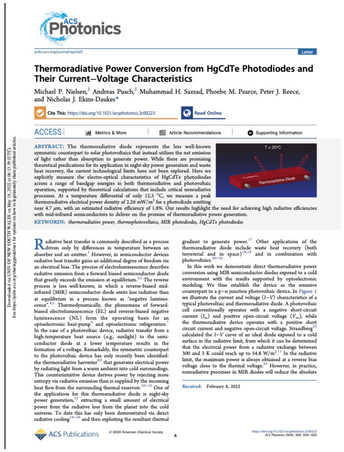
THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

Photons of 1.02 electron volts ($\lambda = 1.2$ microns) are able to produce electron-hole pairs in silicon. In the presence of a *p-n* barrier, these electron-hole pairs are separated and made to do work in an external circuit. All of the light of wavelength shorter than 1.2 microns is potentially useful for generating electron-hole pairs but the efficiency of energy conversion decreases for short wavelengths because the energy above the necessary 1.02 electron



Silicon solar cell:
Pearson, Chapin, Fuller, Bell Labs, **1954**





ACS Photonics
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Letter

Thermoradiative Power Conversion from HgCdTe Photodiodes and Their Current−Voltage Characteristics

Michael P. Nielsen,[‡] Andreas Pusch,[‡] Muhammad H. Sazzad, Phoebe M. Pearce, Peter J. Reece, and Nicholas J. Ekins-Daukes*

Cite This: https://doi.org/10.1021/acsphotonics.2c00223 Read Online

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ABSTRACT: The thermoradiative diode represents the less well-known symmetric counterpart to solar photovoltaics that instead utilizes the net emission of light rather than absorption to generate power. While there are promising theoretical predications for its application in night-sky power generation and waste heat recovery, the current technological limits have not been explored. Here we explicitly measure the electro-optical characteristics of HgCdTe photodiodes across a range of bandgap energies in both thermoradiative and photovoltaic operation, supported by theoretical calculations that include critical nonradiative processes. At a temperature differential of only 12.5 °C, we measure a peak thermoradiative electrical power density of 2.26 mW/m^2 for a photodiode emitting near 4.7 μm, with an estimated radiative efficiency of 1.8%. Our results highlight the need for achieving high radiative efficiencies with mid-infrared semiconductors to deliver on the promise of thermoradiative power generation.

KEYWORDS: *thermoradiative power, thermophotovoltaics, MIR photodiodes, HgCdTe photodiodes*

Radiative heat transfer is commonly described as a process driven only by differences in temperature between an absorber and an emitter.[1] However, in semiconductor devices radiative heat transfer gains an additional degree of freedom via an electrical bias. The process of electroluminescence describes radiative emission from a forward biased semiconductor diode that greatly exceeds the emission at equilibrium.[2,3] The reverse process is less well-known, in which a reverse-biased mid-infrared (MIR) semiconductor diode emits less radiation than at equilibrium in a process known as "negative luminescence".[4,5] Thermodynamically, the phenomena of forward-biased electroluminescence (EL) and reverse-biased negative luminescence (NL) form the operating basis for an optoelectronic heat-pump[6] and optoelectronic refrigeration.[7] In the case of a photovoltaic device, radiative transfer from a high-temperature heat source (e.g., sunlight) to the semiconductor diode at a lower temperature results in the formation of a voltage. Remarkably, the symmetric counterpart to the photovoltaic device has only recently been identified: the thermoradiative harvester[8,9] that generates electrical power by radiating light from a warm ambient into cold surroundings. This counterintuitive device derives power by rejecting more entropy via radiative emission than is supplied by the incoming heat flow from the surrounding thermal reservoir.[10−12] One of the applications for this thermoradiative diode is night-sky power generation,[13] extracting a small amount of electrical power from the radiative loss from the planet into the cold universe. To date this has only been demonstrated via direct radiative cooling[14−16] and then exploiting the resultant thermal gradient to generate power.[17] Other applications of the thermoradiative diode include waste heat recovery (both terrestrial and in space)[18,19] and in combination with photovoltaics.[20−22]

In this work we demonstrate direct thermoradiative power conversion using MIR semiconductor diodes exposed to a cold environment with the results supported by optoelectronic modeling. We thus establish the device as the emissive counterpart to a p−n junction photovoltaic device. In Figure 1 we illustrate the current and voltage (I−V) characteristics of a typical photovoltaic and thermoradiative diode. A photovoltaic cell conventionally operates with a negative short-circuit current (I_{sc}) and positive open-circuit voltage (V_{oc}), while the thermoradiative device operates with a positive short circuit current and negative open-circuit voltage. Strandberg[23] calculated the I−V curve of an ideal diode exposed to a cold surface in the radiative limit, from which it can be determined that the electrical power from a radiative exchange between 300 and 3 K could reach up to 54.8 W/m^2.[11] In the radiative limit, the maximum power is always obtained at a reverse bias voltage close to the thermal voltage.[24] However, in practice, nonradiative processes in MIR diodes will reduce the absolute

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ACS Photonics XXXX, XXX, XXX−XXX

Thermoradiative diode:
Sazzad, Reece, Pusch, Nielsen, Ekins-Daukes, Pearce, UNSW, **2022**

- Thermoradiative power generation has been demonstrated with mW.m^{-2} electrical power density.
- In the radiative limit, thermoradiative power can be generated at levels of tens W.m^{-2}
- Practical thermoradiative devices delivering W.m^{-2} demand very high radiative efficiency.