Highly Efficient Thin Film Photovoltaics for Clean Energy Generation

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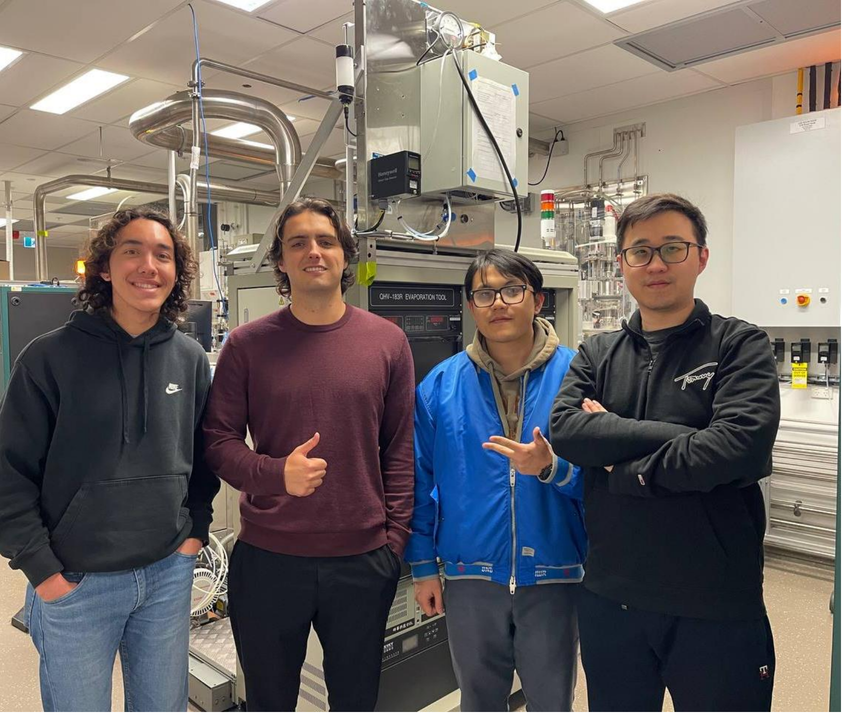
International Research Experiences for Students (IRES)

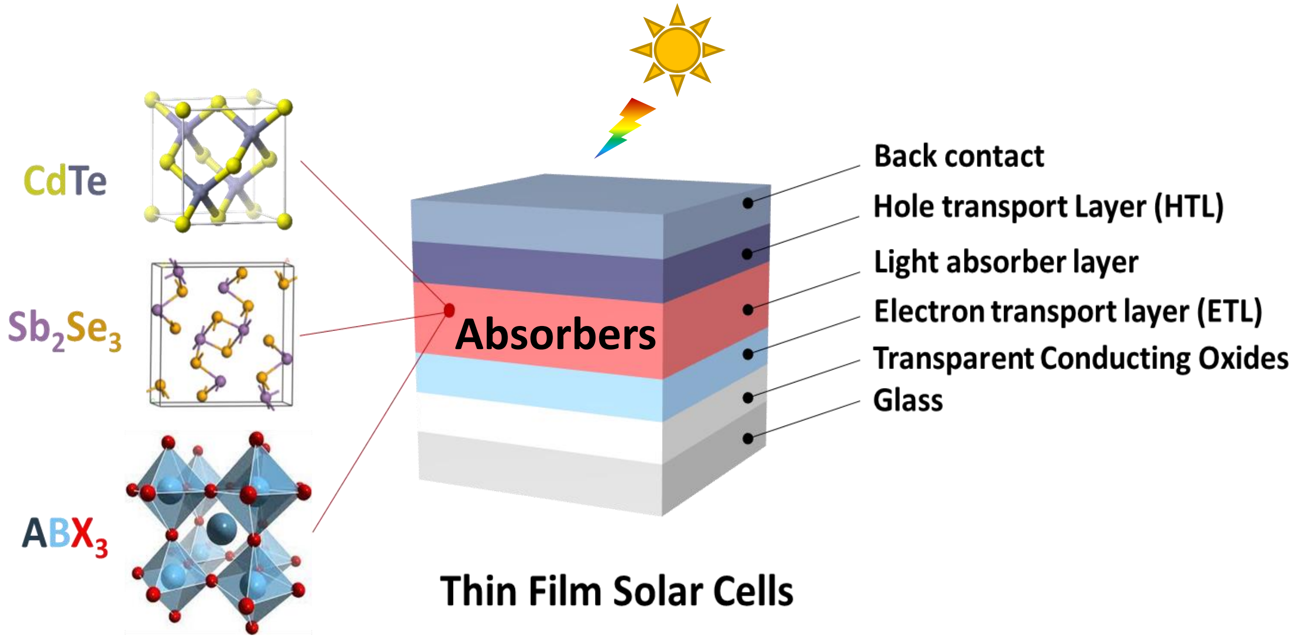

QHV-183R EVAPORATION TOOL


ORIGIN
Coffee


KIYON

Outline

- **Climate Change and Solar Energy**
  - Climate Change
  - Why solar?
  - Solar cells.
- **Chalcogenides Thin Films Solar Cells**
  - CdTe Thin Film Solar Cell
    - Doping Strategy: ex-situ Group V doping
  - Sb_2Se_3 Thin Film Solar Cells
    - Close space sublimated Sb_2Se_3 solar cells.
- **Carbon-based Perovskite Solar Cell**
  - Stability and High Efficiency
  - Low-cost Manufacturing Approach



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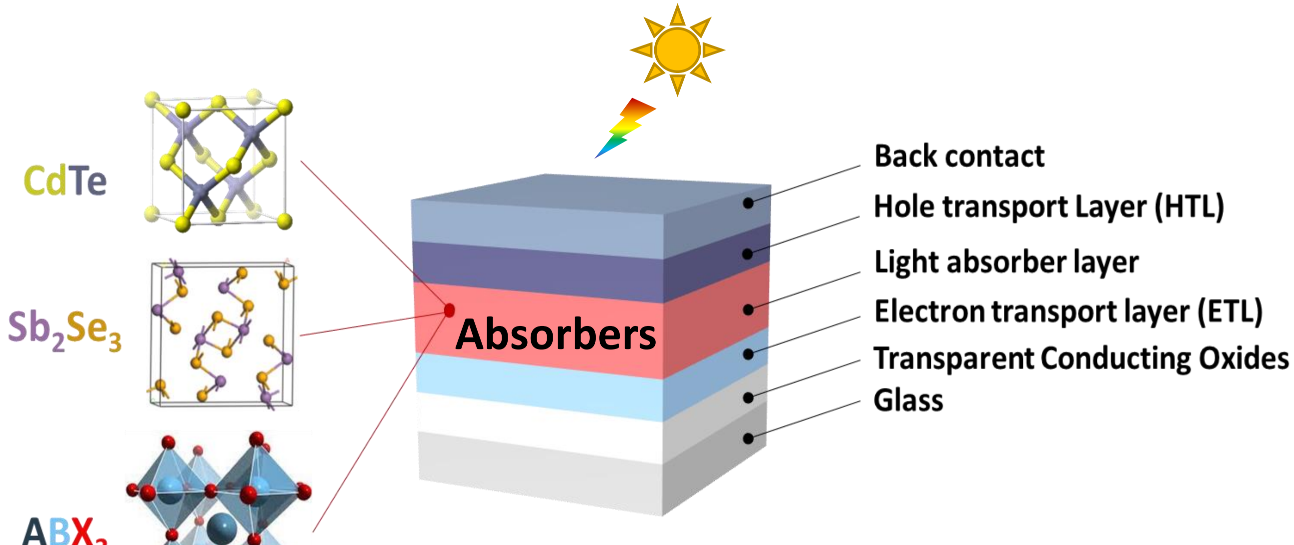


Thin Film Solar Cells

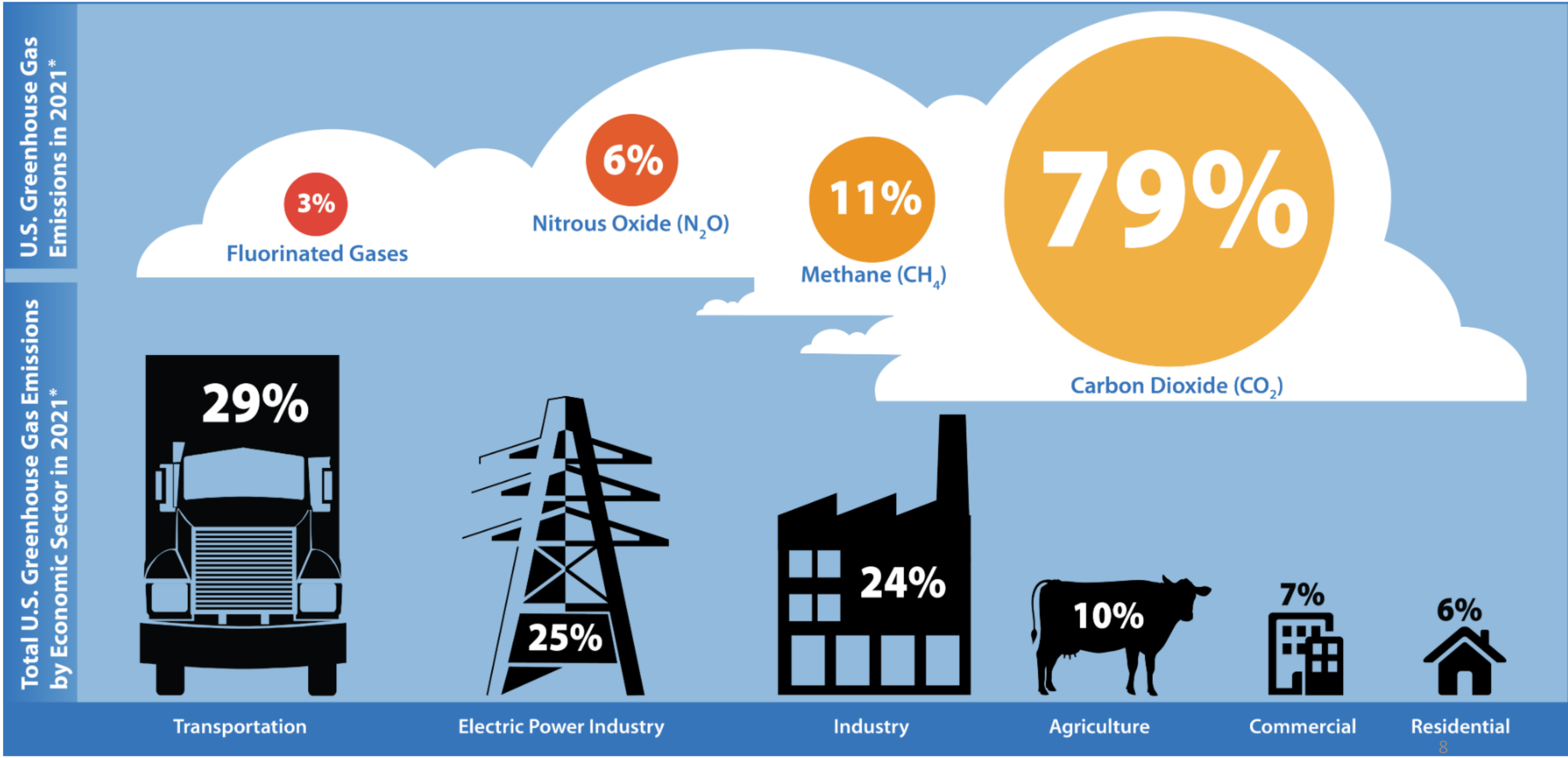
(47.7 °C)


Clear Channel Outdoor
05:20 pm
118°
003050
Clear Channel


10-YEAR-OLD IN DIES AFTER HIKE
AIRLIFTED OFF SOUTH MOUNTAIN AS TEMPERATURES TOPPED 108 DEGREES
3
9:00 106°
FORECAST
PAYSON
WED 94°/67°
THU 98°/67°
FRI 100°/67°

(42.2 °C)

Greenhouse Gas Emissions for Climate Change



*Percentages may not add to 100% due to independent rounding and the way the inventory quantifies U.S. territories (not shown) as a separate sector. Percentages are based on gross total emissions excluding emissions and removals from the land use, land-use change and forestry sector.

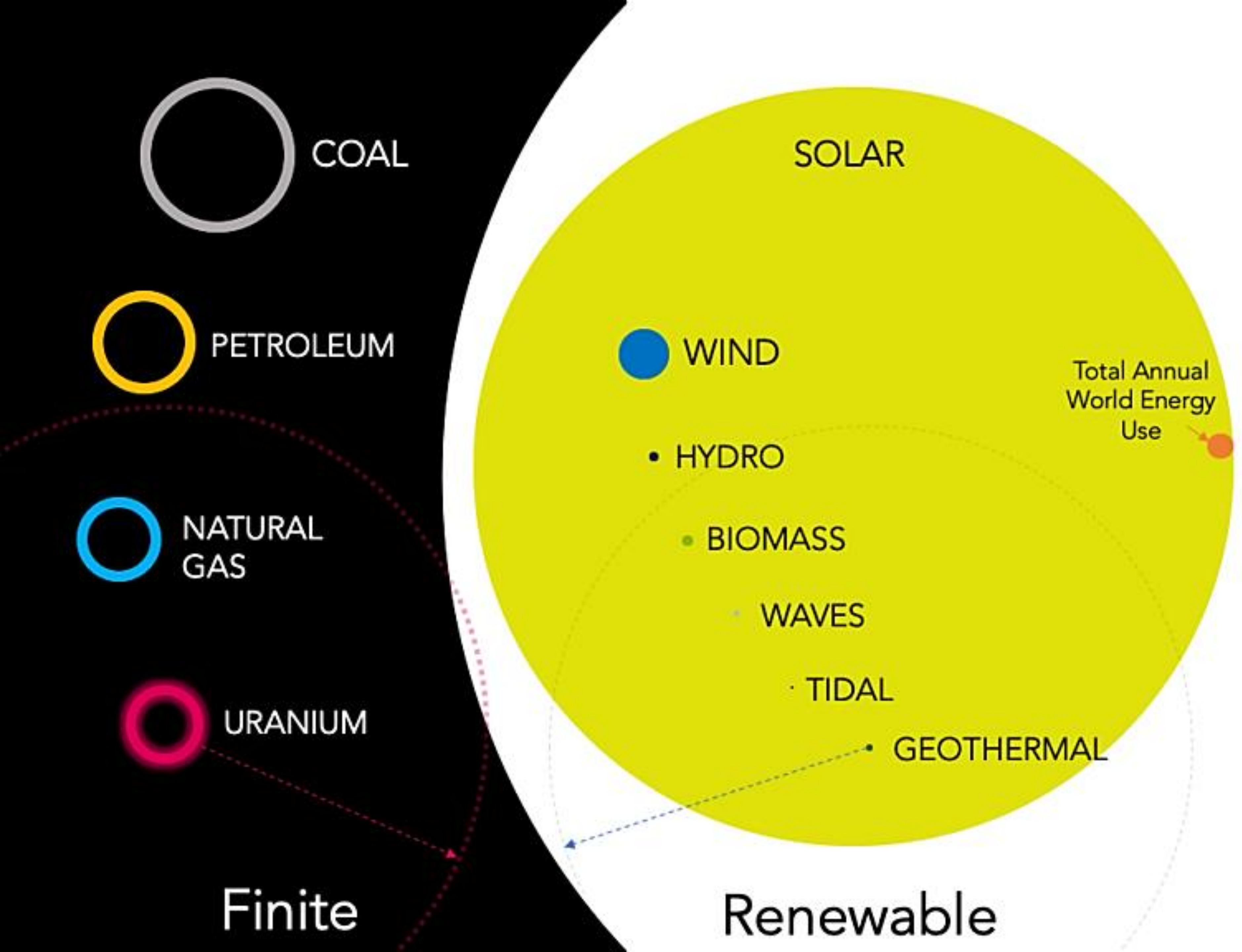
https://cfpub.epa.gov/ghgdata/inventoryexplorer/

Our GHG Goal

30%
REDUCTION
from a 2019 baseline
by 2030

&

CARBON
NEUTRAL
by 2050



WORLD ENERGY USE

2021 Use	20 TWy/y

RENEWABLES

Solar	23,000 TWy/y
Wind	75-130 TWy/y
Waves	0.2-2 TWy/y
Hydro	3-4 TWy/y
Biomass	2-6 TWy/y
Geothermal	0.2-3++ TWy/y
Tidal	0.3 TWy/y

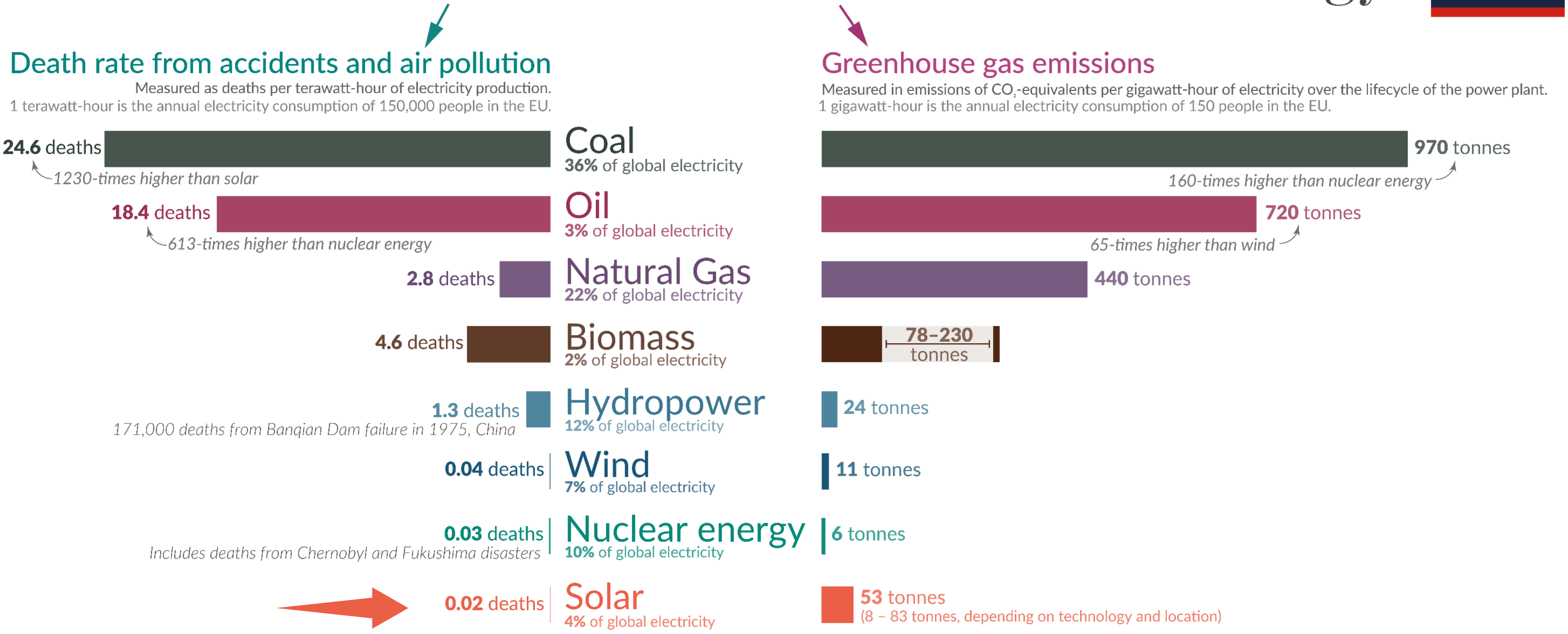
FINITE

Coal	830 TWy
Natural Gas	220 TWy
Petroleum	335 Twy
Uranium	185++ TWy

Source: Marc Perez & Richard Perez: *A Fundamental Look at the Supply Side Energy Reserves for the Planet*; Rendered: The Freeing Energy Project

What are the safest and cleanest sources of energy?

Our World in Data



Death rates from fossil fuels and biomass are based on state-of-the art plants with pollution controls in Europe, and are based on older models of the impacts of air pollution on health. This means these death rates are likely to be very conservative. For further discussion, see our article: OurWorldinData.org/safest-sources-of-energy. Electricity shares are given for 2021.

Data sources: Markandya & Wilkinson (2007); UNSCEAR (2008; 2018); Sovacool et al. (2016); IPCC AR5 (2014); UNECE (2022); Ember Energy (2021).

OurWorldinData.org – Research and data to make progress against the world's largest problems.

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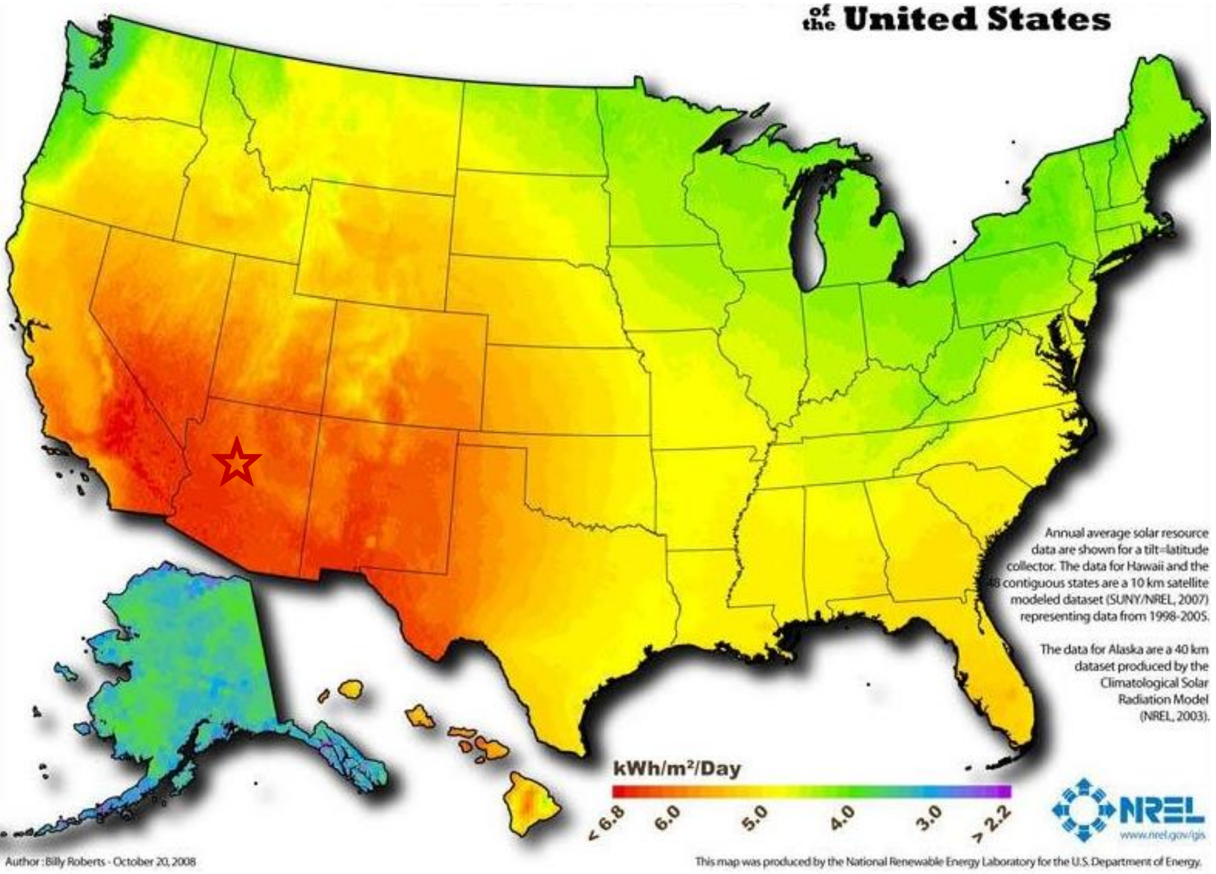
https://ourworldindata.org/cheap-renewables-growth

~10 mins Solar Energy Received on Earth (1.5×10^{12} TWh/year)

1 Year The World Used Electricity (~3×10^{5} TWh/year)

Solar Energy in US & Australia



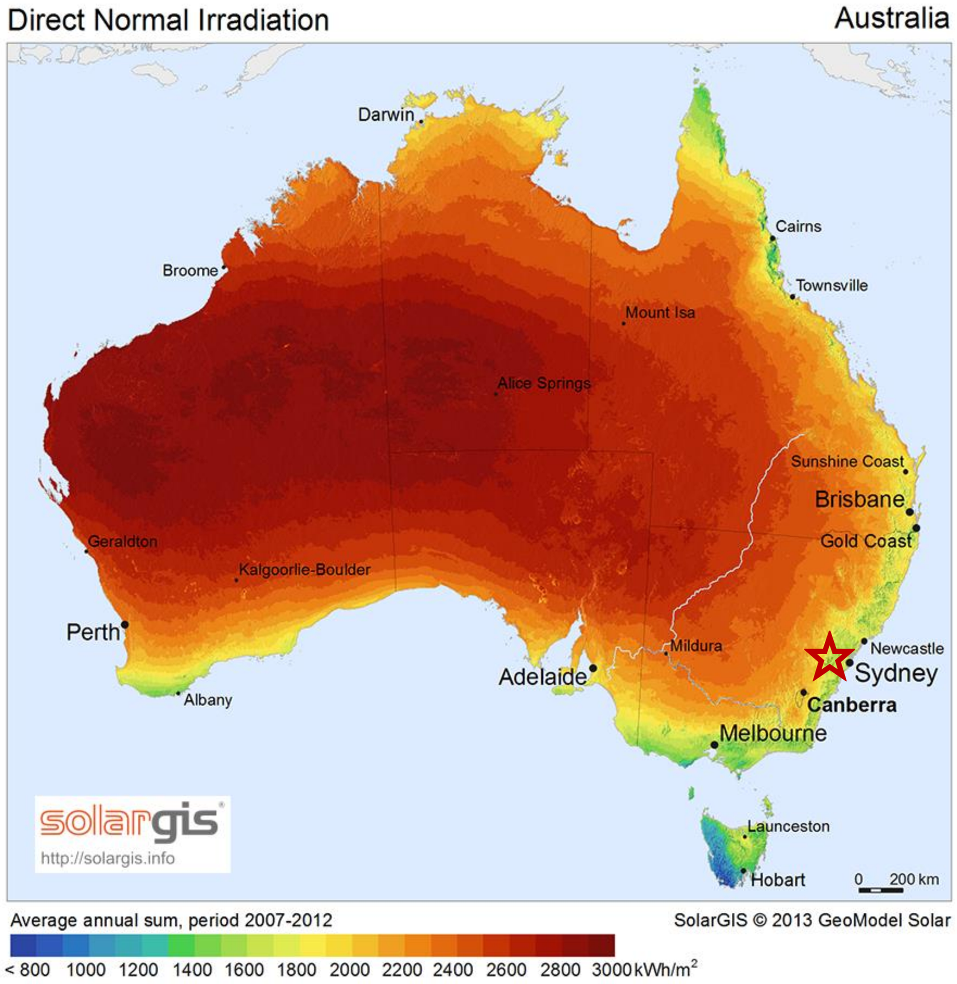
Annual average solar resource data are shown for a tilt=latitude collector. The data for Hawaii and the 48 contiguous states are a 10 km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005.

The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

Author : Billy Roberts - October 20, 2008

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy.

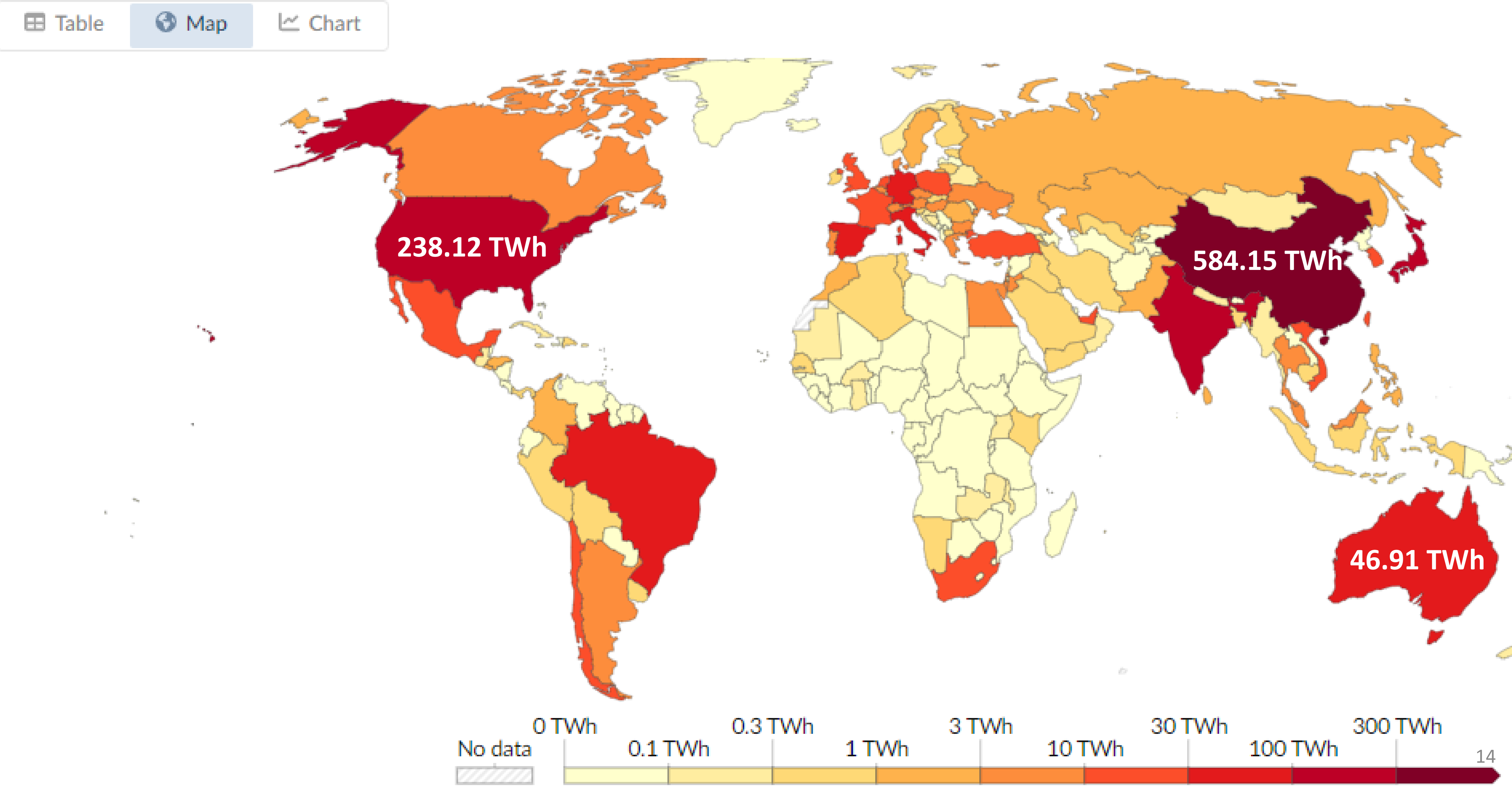
9.834 million km²



7.688 million km²

Solar power generation, 2023

Electricity generation from solar, measured in terawatt-hours (TWh) per year.

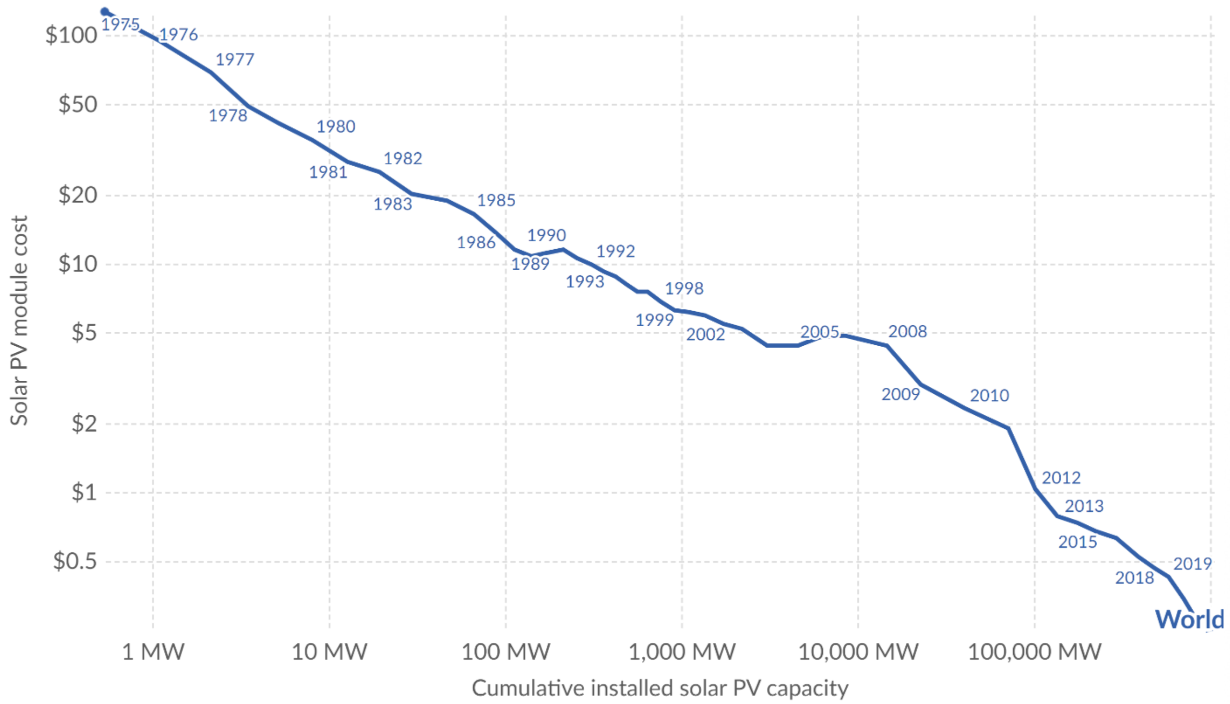


Future of Solar Energy: Price

Solar (photovoltaic) panel prices vs. cumulative capacity

This represents the learning curve for solar panels. This data is expressed in US dollars per Watt, adjusted for inflation. Cumulative installed solar capacity is measured in megawatts.

Our World in Data

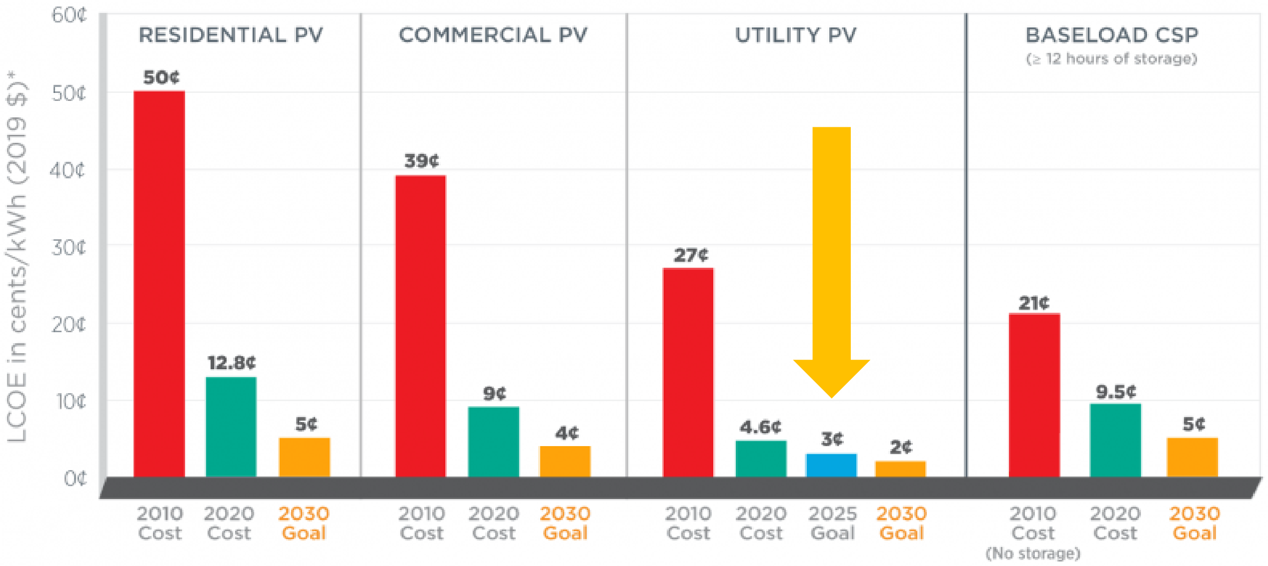


Data source: International Renewable Energy Agency (2023); Nemet (2009); Farmer and Lafond (2016)
Note: Data is expressed in constant 2022 US$ per Watt.
OurWorldInData.org/energy | CC BY

1975 → 2022

Solar Energy Technologies Office Progress and Goals

Photovoltaics (PV) and Concentrating Solar-Thermal Power (CSP)



*Levelized cost of energy (LCOE) PV progress and targets are calculated based on average U.S. climate and without the Investment Tax Credit or state/local incentives.

https://ourworldindata.org/grapher/solar-pv-prices-vs-cumulative-capacity?time=earliest..2022

https://www.georgiapower.com/residential/billing-and-rate-plans/pricing-and-rate-plans/residential-service.html

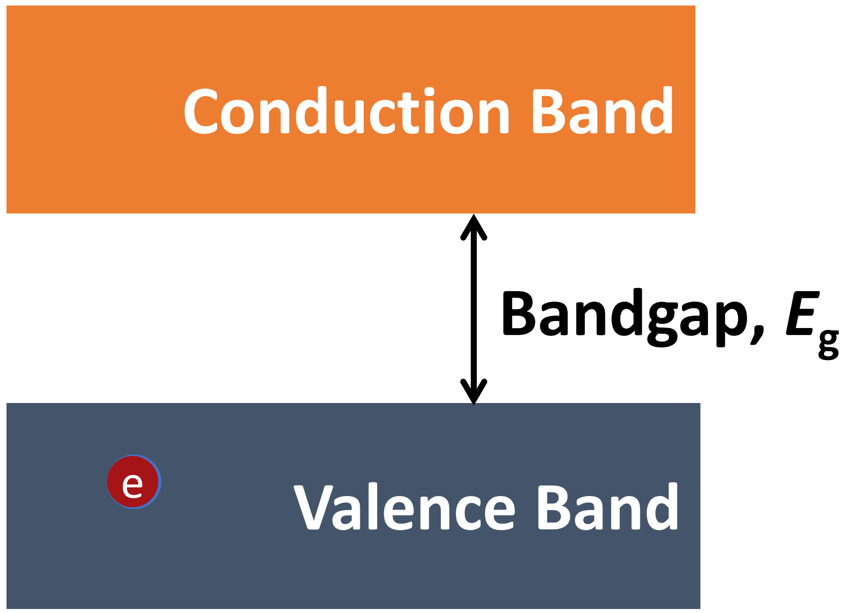
ASU's sustainability practices earn No. 1 ranking from esteemed higher-education rating system

UNSW flicks the switch on 100% renewable electricity

Solar Cell: Photovoltaic Effect

Semiconductors

Recombination


Conduction Band

Bandgap, E_g

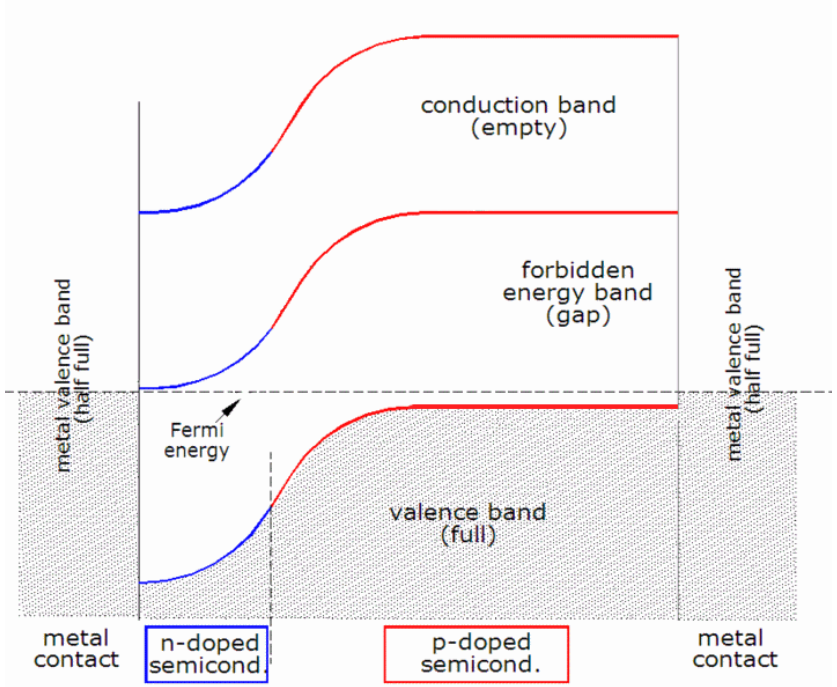
Valence Band

Since 1839

(1820-1891)

Semiconductors with suitable bandgap for light absorption, e.g., Si~1.1eV, CdTe~1.4 eV, Perovskite Halides ~ 1.5 eV

Sillicon Solar Cells



***p-n* junction**


1954

Something New Under the Sun. It's the Bell Solar Battery, made of thin discs of specially treated silicon, an ingredient of common sand. It converts the sun's rays directly into usable amounts of electricity. Simple and trouble-free. (The storage batteries beside the solar battery store up its electricity for night use.)

Bell System Solar Battery Converts Sun's Rays into Electricity!

Bell Telephone Laboratories invention has great possibilities for telephone service and for all mankind

Ever since Archimedes, men have been searching for the secret of the sun.

For it is known that the same kindly rays that help the flowers and the grains and the fruits to grow also send us almost limitless power. It is nearly as much every three days as in all known reserves of coal, oil and uranium.

If this energy could be put to use — there would be enough to turn every wheel and light every lamp that mankind would ever need.

The dream of ages has been brought closer by the Bell System Solar Battery. It was invented at the Bell Telephone Laboratories after long research and first announced in 1954. Since then its efficiency has been doubled and its usefulness extended.

There's still much to be done before the battery's possibilities in telephony and for other uses are fully developed. But a good and pioneering start has been made.

The progress so far is like the opening of a door through which we can glimpse exciting new things for the future. Great benefits for telephone users and for all mankind may come from this forward step in putting the energy of the sun to practical use.

BELL TELEPHONE SYSTEM

2024

Si vs Thin film Solar Cells

Si solar cells and module manufacturing 2-3 days (~150 μm)

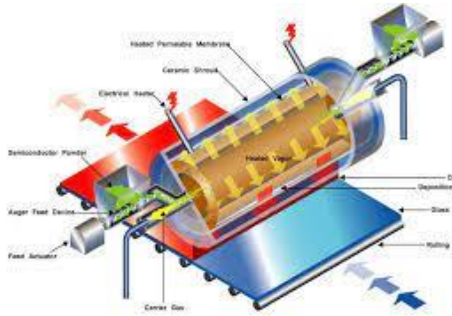
Polysilicon → Si Ingot → Wafer → Si Cell → Module → System





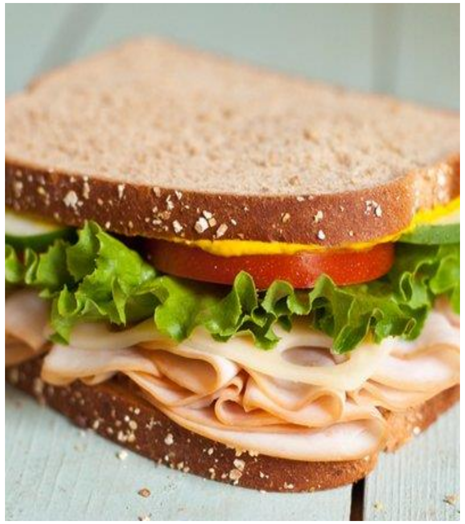

CdTe Thin film solar cells and module manufacturing 2-3 hours (1-3 μm)

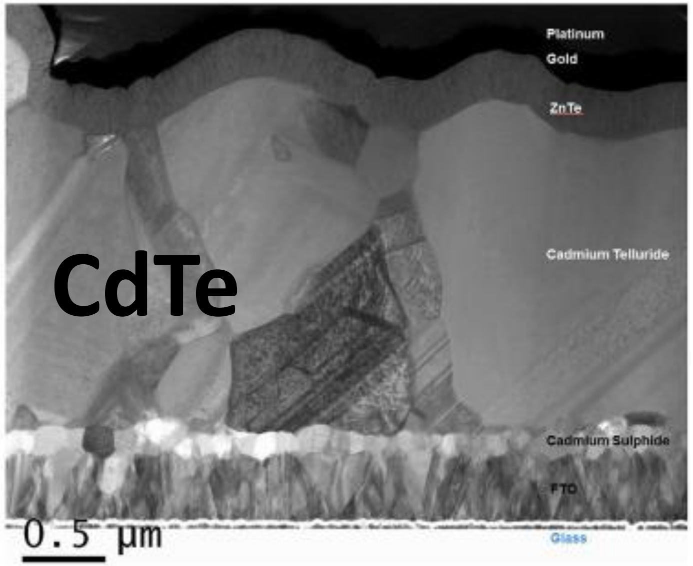
FTO Glass → Absorber Deposition → Chemical treatment → Metal contact → Module → System

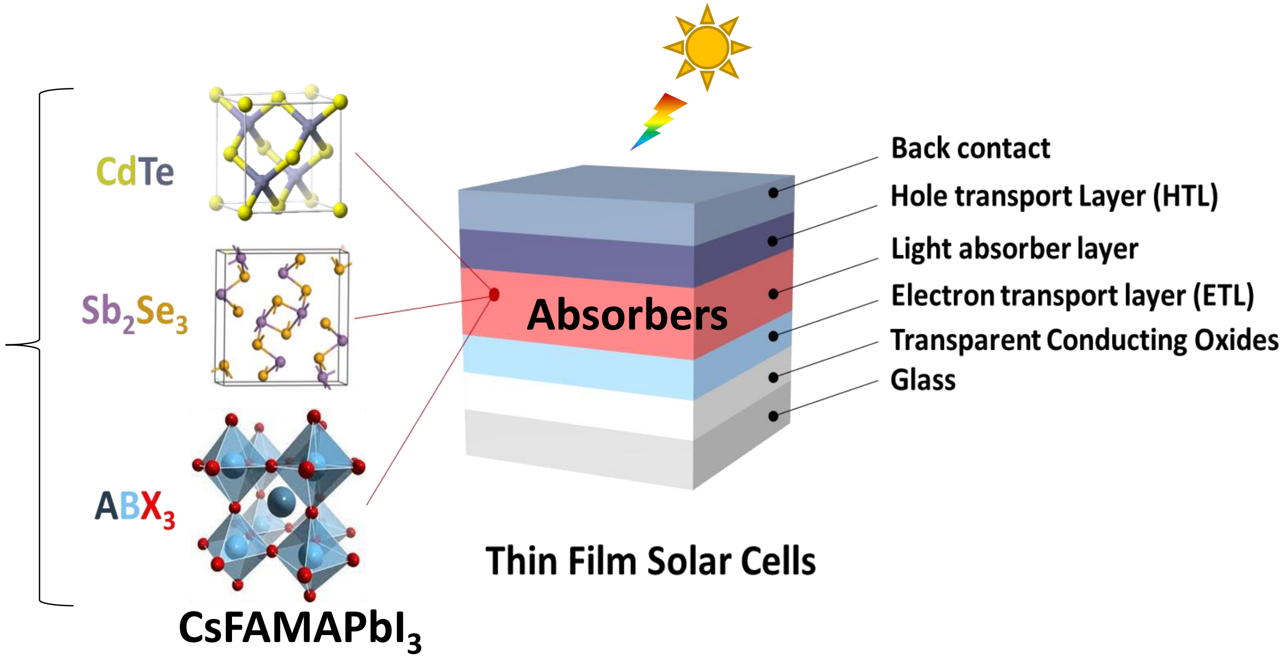


Thin Film Photovoltaics (PV) Solar Cells





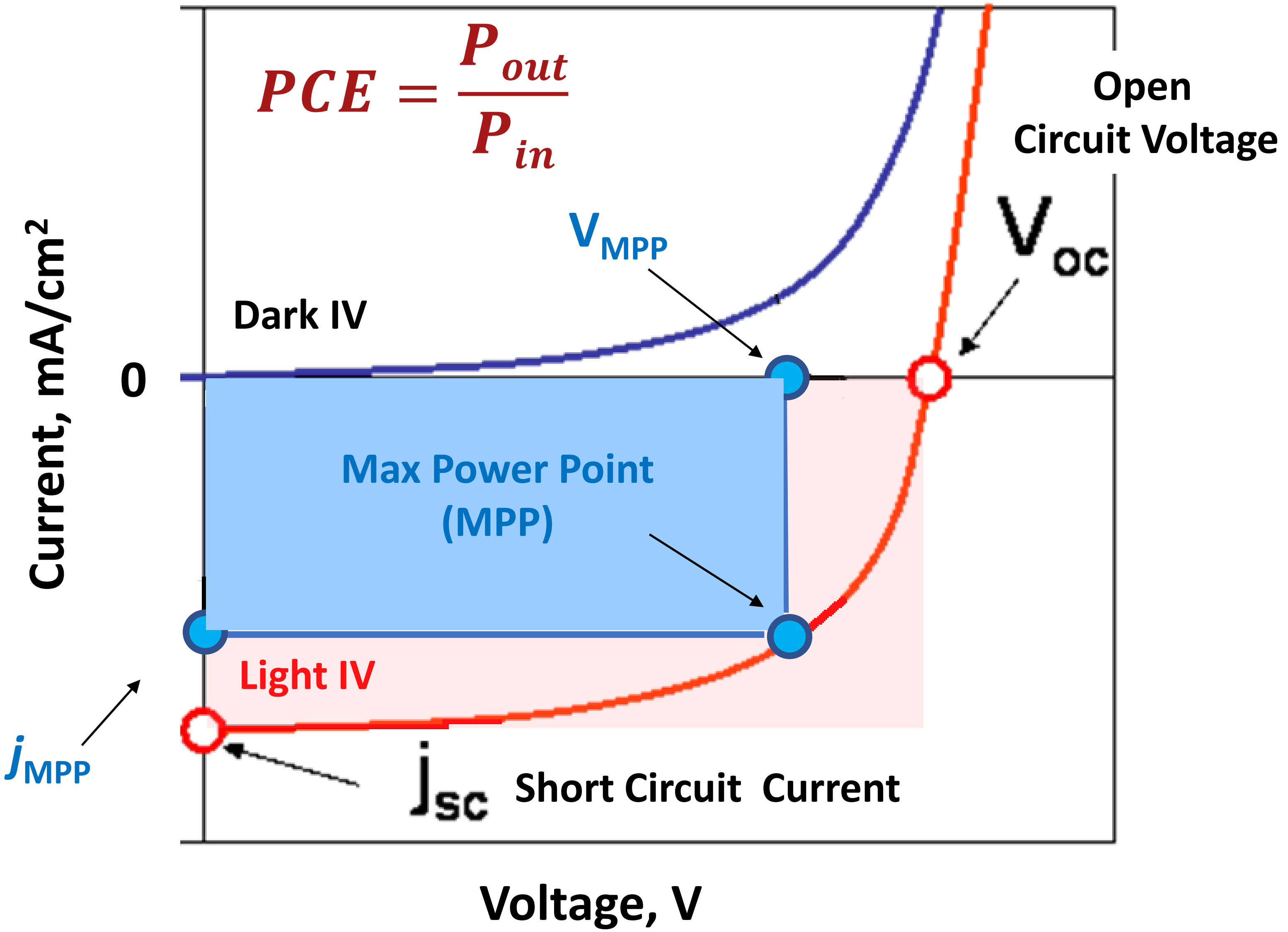
Vacuum, V. 139, P, 159, 2017



Thin Film Solar Cells

Solar Cell Efficiency Measurement: Current-Voltage (I-V) Curve

Power conversion efficiency (PCE)

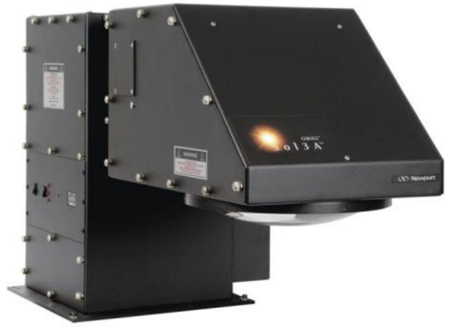


Fill Factor (*FF*)

$$FF = \frac{\text{Blue Area}}{\text{Red Area}} = \frac{V_{MPP} \times j_{MPP}}{V_{oc} \times j_{sc}}$$

$$PCE = (V_{oc} \times j_{sc} \times FF)/Pin$$

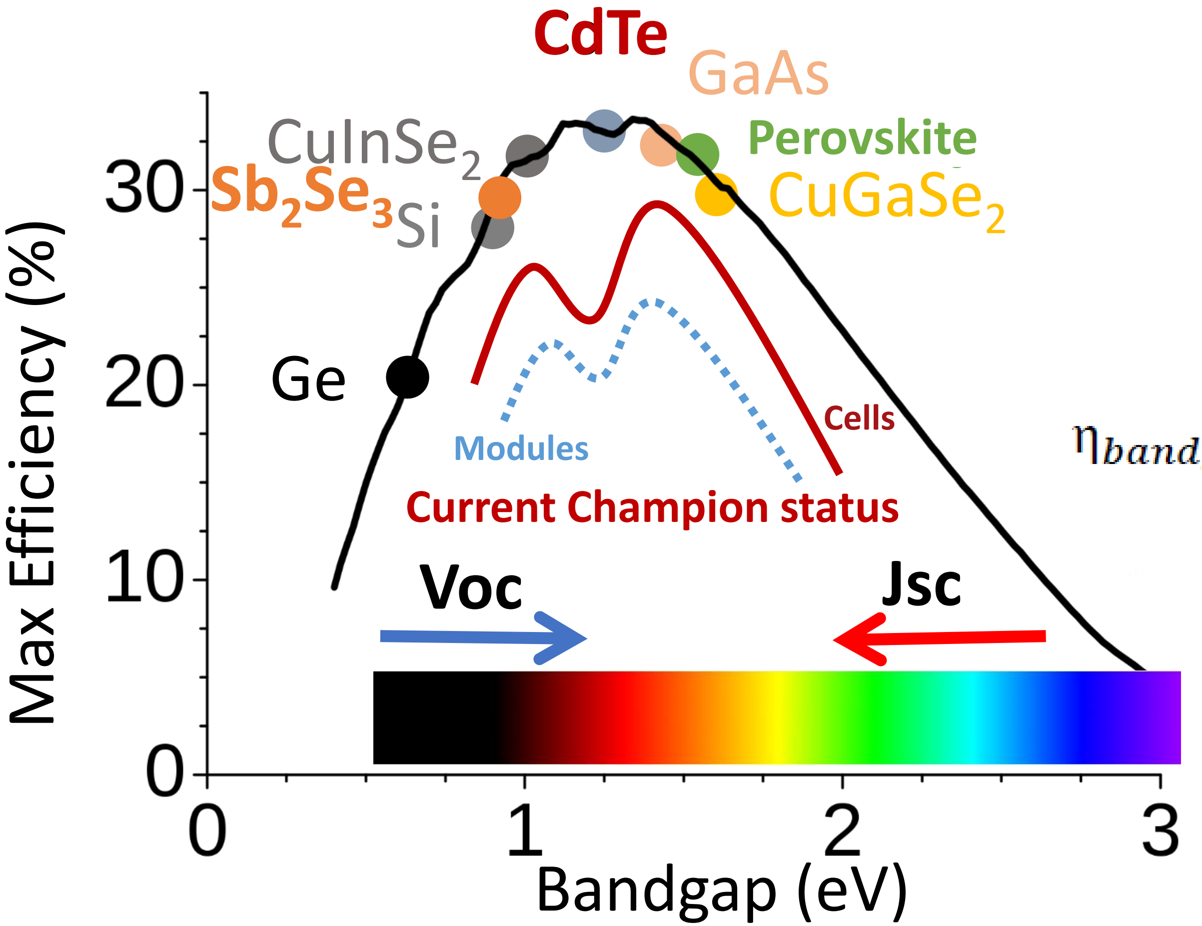
(1 Sun in lab, P_{in} =100 mW/cm²)



Solar Simulator

Shockley–Queisser Limit (SQL) for Efficiency

Single Junction Solar Cell : Theoretical PCE ~ 32% @ 1.4 eV

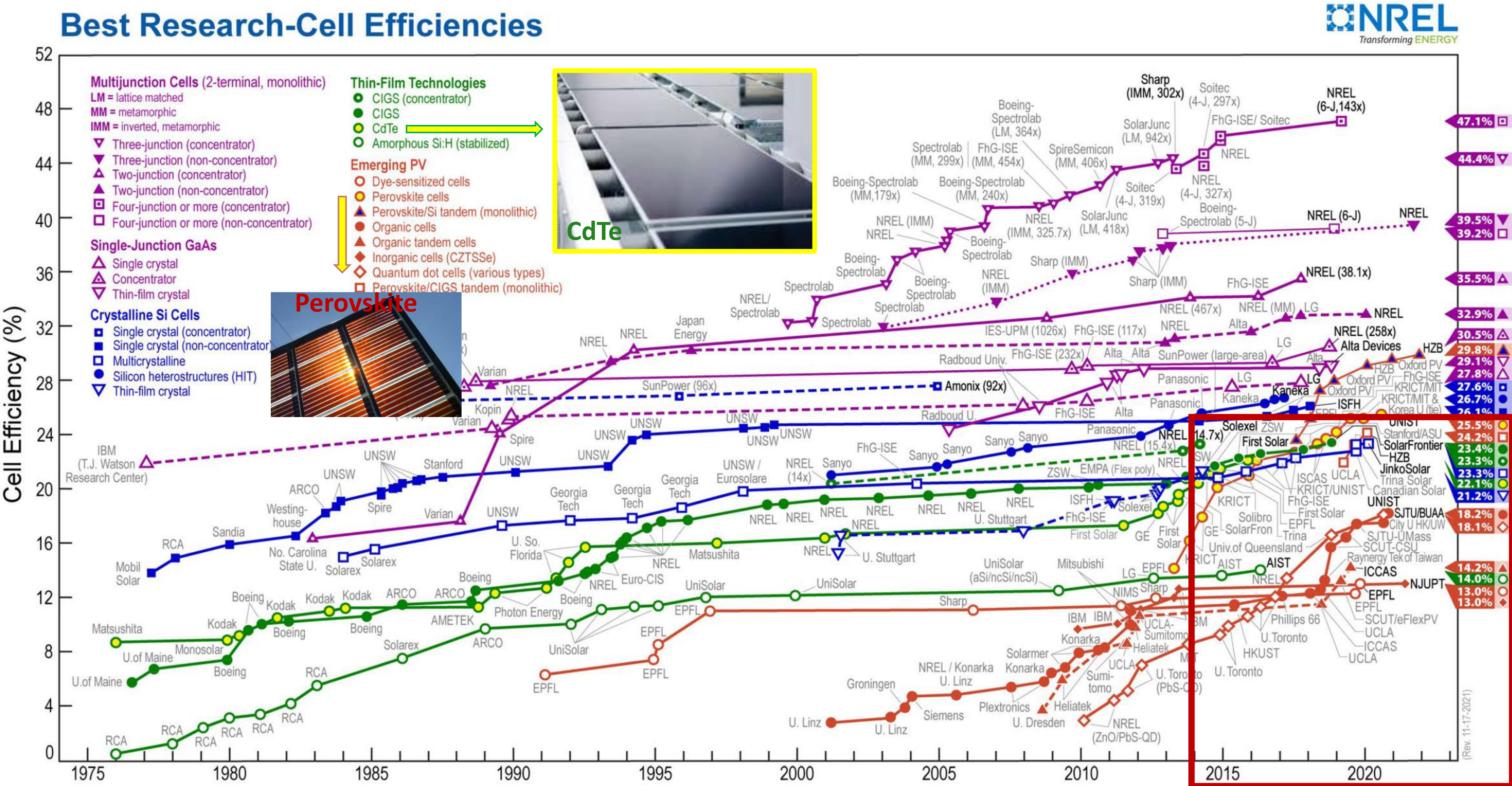


$$\eta_{bandgap}(\epsilon_{gap}, T_s) = \frac{\epsilon_{gap} \int_{\epsilon_{gap}}^{\infty} \frac{2\pi}{h^3 c^2} \frac{\epsilon^2}{e^{\epsilon/kT_s} - 1} d\epsilon}{\int_0^{\infty} \frac{2\pi}{h^3 c^2} \frac{\epsilon^3}{e^{\epsilon/kT_s} - 1} d\epsilon}$$

Max power when absorb visible light (max V_{oc}) and few traps (max J_{sc})

W. Shockley and H. J. Queisser, *J. Appl. Phys.*, 1961, **32**, 510–519.

1% of Efficiency improvement can reduce 5% cost of Solar Cell



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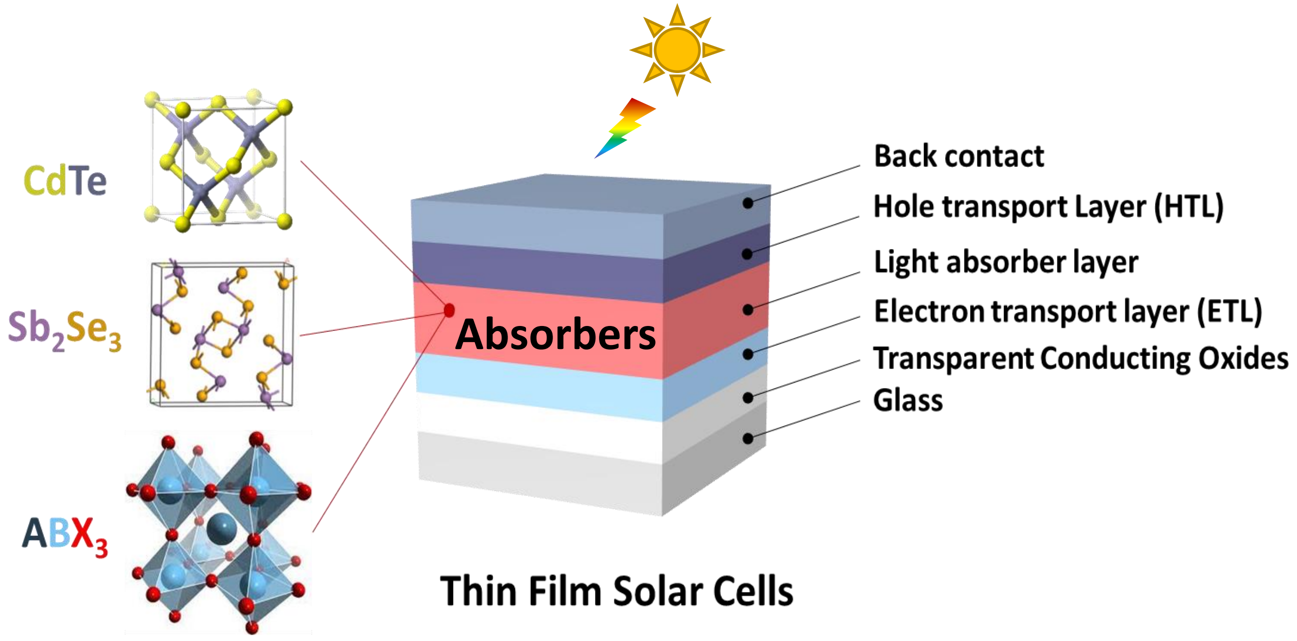
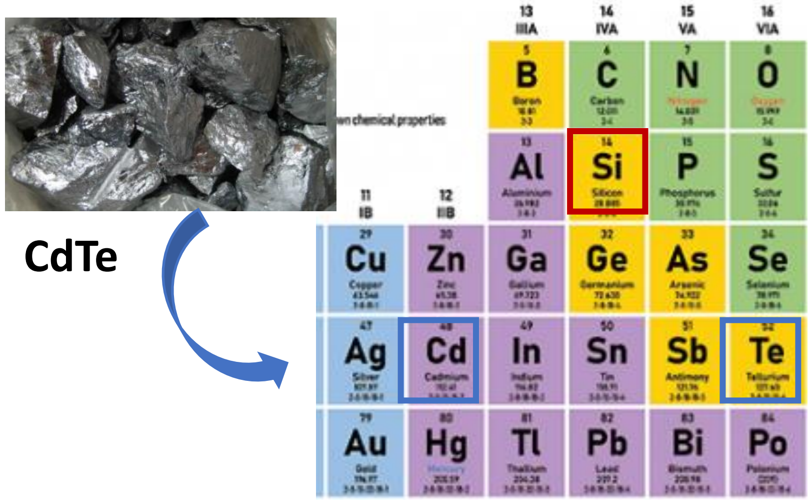
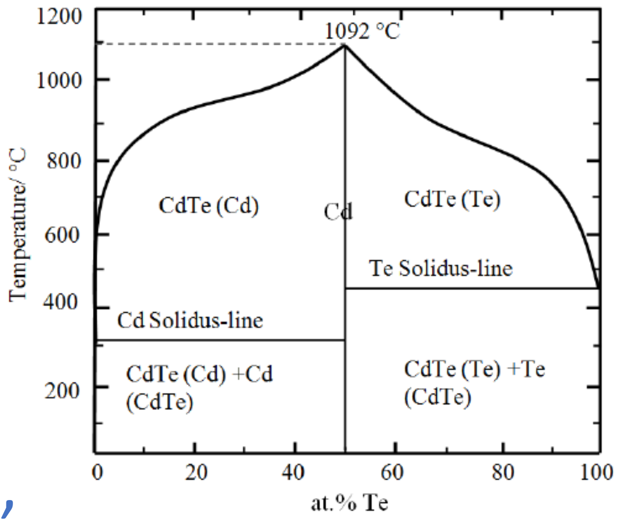
- Carbon-based Perovskite Solar Cell
  - Marriage of Stability and High Efficiency
  - Low-cost Manufacturing Approach



Thin Film Solar Cells

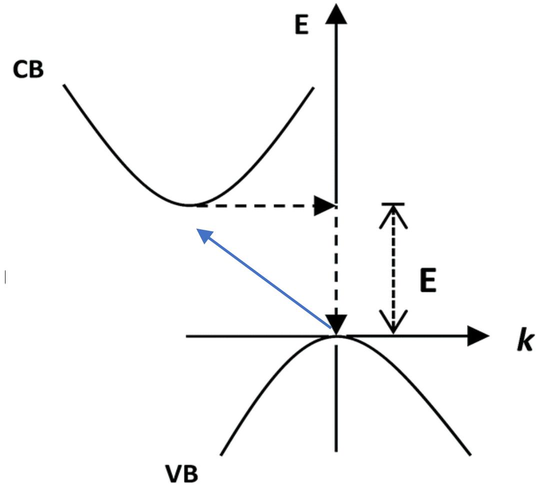
CdTe Thin Film Solar Cells



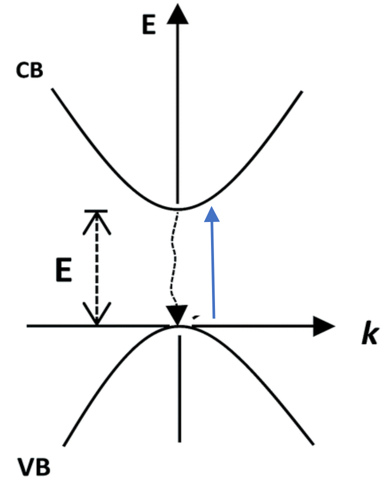


550MW AC, **Topaz Solar Farm**, San Luis, CA, USA
First Solar developed (Area: 25 km^2)
9M Modules, 160K Homes, 377K Tons CO$_2$ displaced

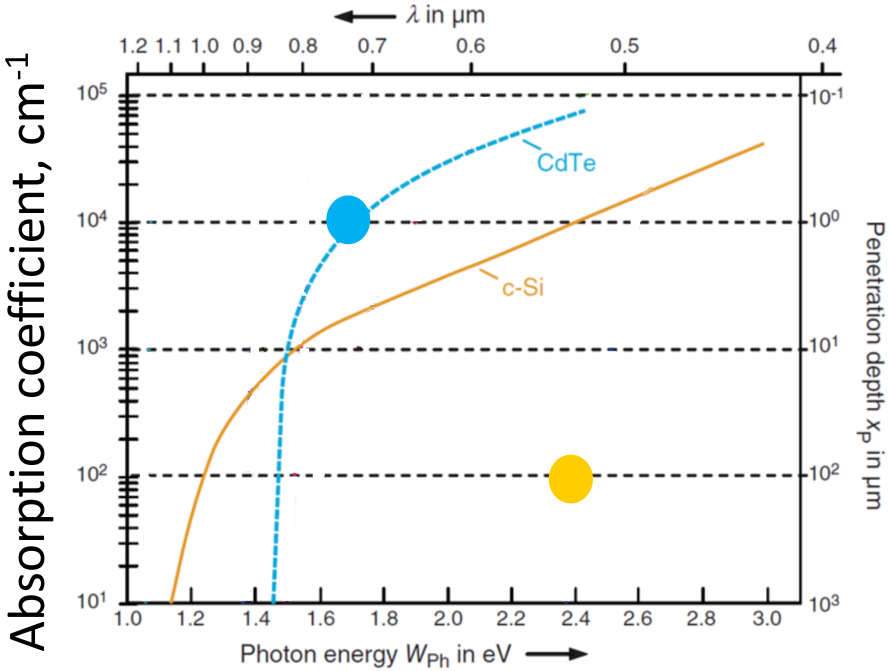
Cadmium Telluride = “CadTel”



Si: Indirect Bandgap

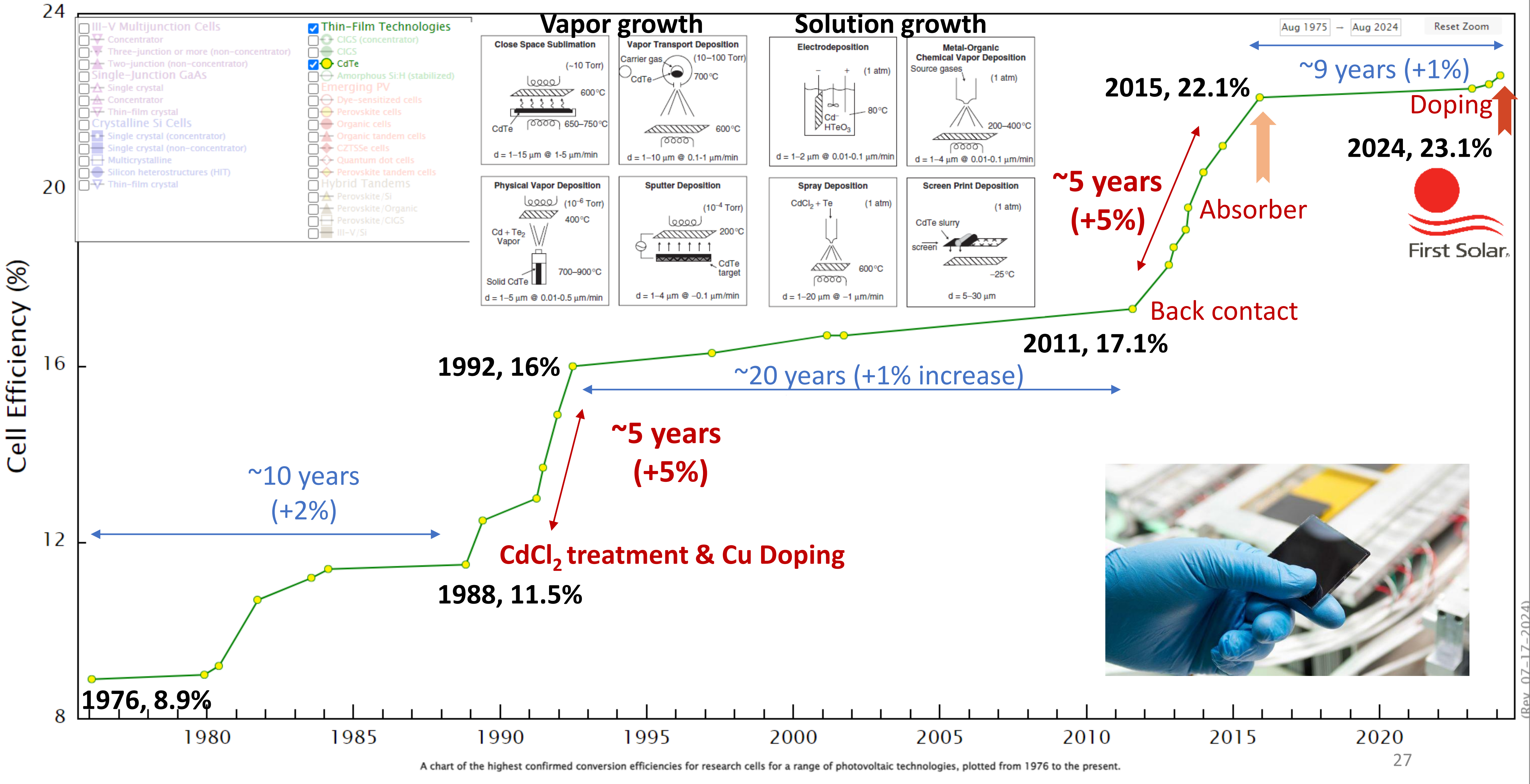


CdTe: Direct Bandgap



Toxic

Best Research-Cell Efficiencies



A chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present.

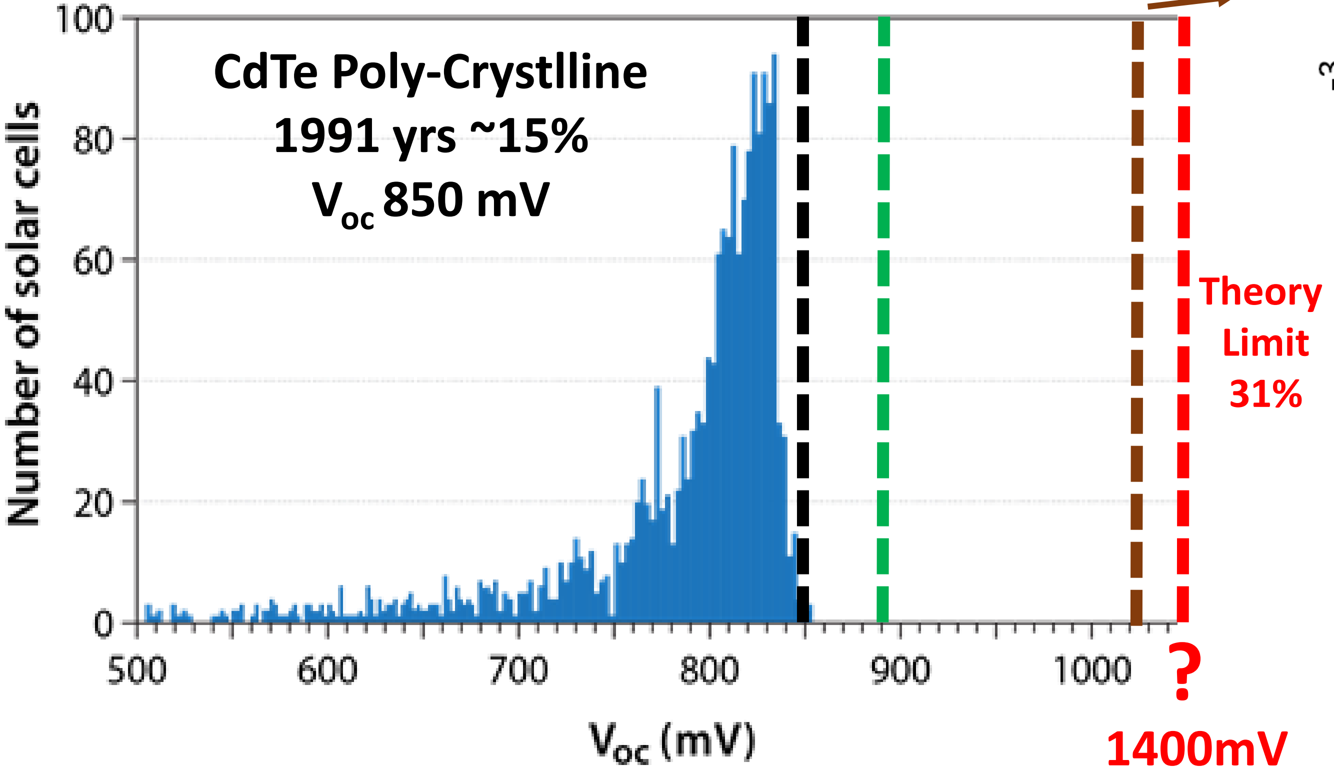
The chart displays record research cell efficiencies for five major technologies: crystalline silicon cells, single-junction gallium arsenide cells, multijunction cells, thin films, and emerging PV. Efficiencies have increased across all technologies over the last 50 years.

Major Challenges in Polycrystalline CdTe Solar Cells

Doped Poly-Crystalline
22.6% (2024)
V_{oc} 898.9 mV

Mono-Crystalline
17%
V_{oc} 1096 mV

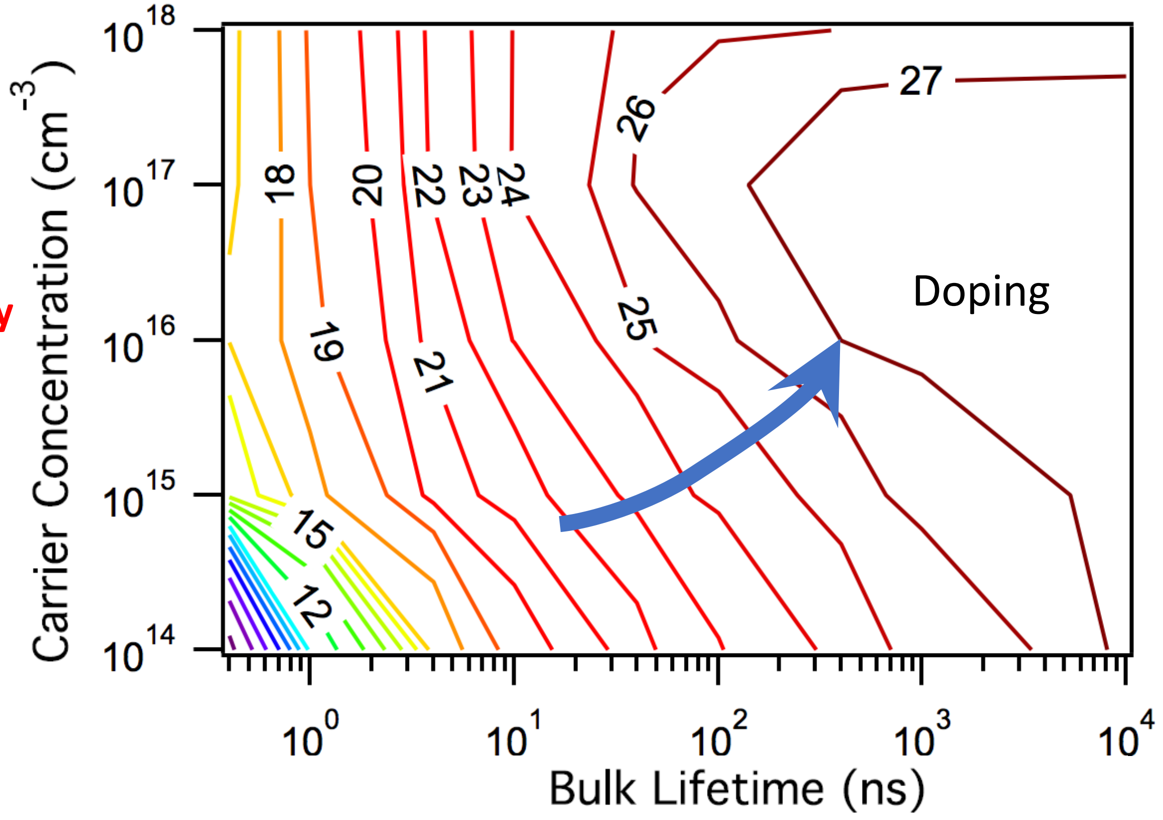
- **Open circuit Voltage: Voc**



CdTe Poly-Crystlline
1991 yrs ~15%
V_{oc} 850 mV

Theory
Limit
31%

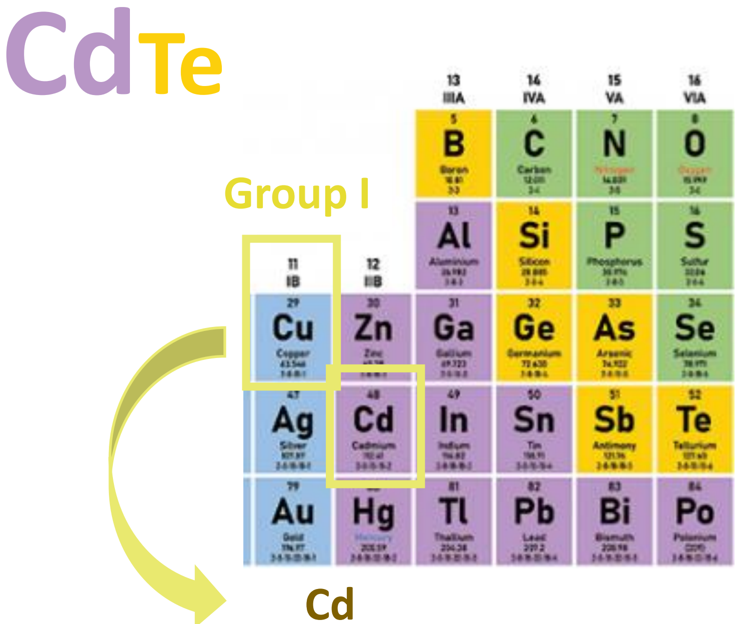
?
1400mV
S-Q limit



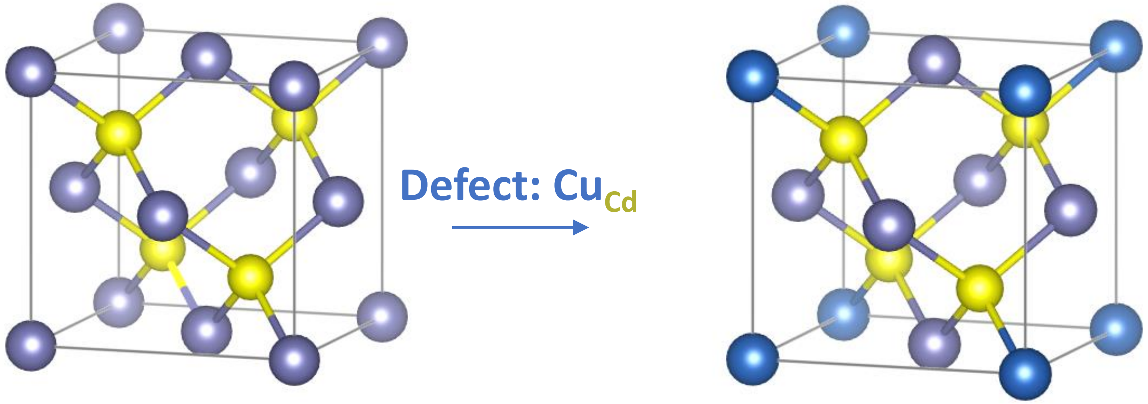
Burst etc, Nature Energy,1, 16055, 2016; Duenow, etc. APL, 105, 053903, 2014

Doping in CdTe: Traditional Cu in Cd Site

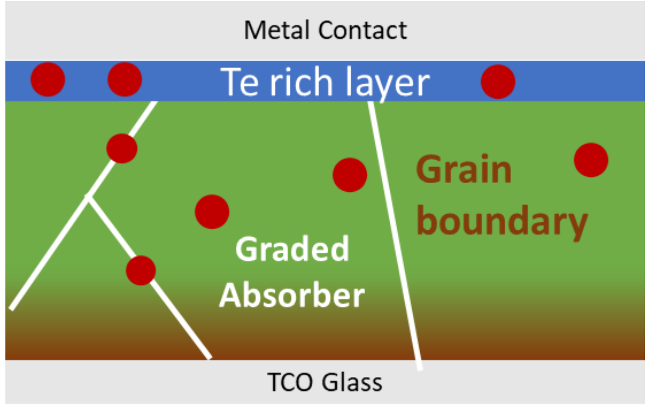
"In semiconductor production, **doping** is the ***intentional introduction of impurities*** into an intrinsic semiconductor for the purpose of modulating its electrical, optical, and structural properties."--Wikipedia



$2Cu + Te = Cu_2Te$



$$Cu^+ + V_{Cd} = (Cu_{Cd})^- + h^+$$



Dopants ● Cu ions

Cu doping in Cd site:
CuCl, Cu:ZnTe , etc as dopants sources

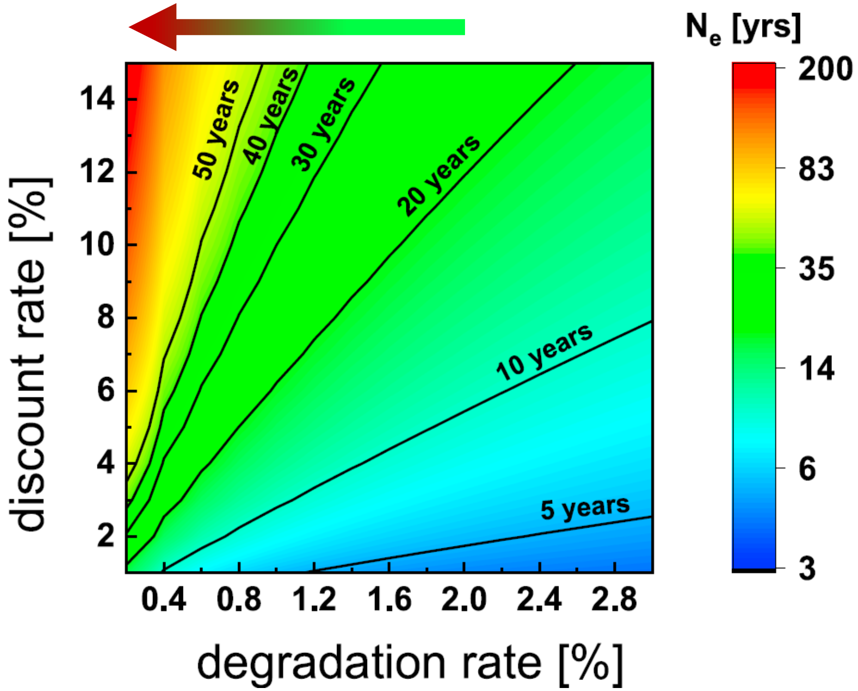
Cu doping Challenges in CdTe Device

- *1. Fast Cu diffusion rate* leads to the fast degradation of device performance
  - Stability issue: Efficiency degrades 20% in 25 years.

How to improve the module lifetime beyond 25 years?

- 2. Cu doping has a *low carrier lifetime and carrier concentration.*
  - Cu associated accepters are difficult to activate (less than 1%).
  - *Low Voc* ~870mV in solar module

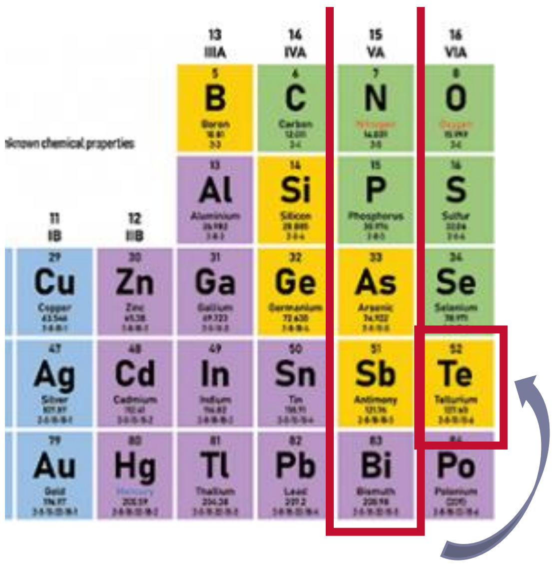
How to improve the Voc beyond 900 mV of polycrystal CdTe?



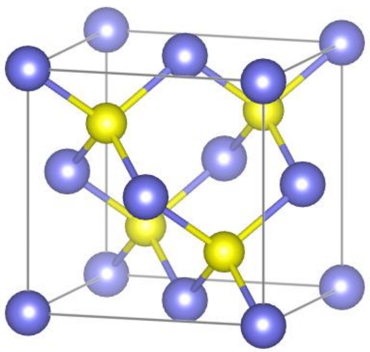
Peters et al., Joule 5, 1–17. 2021

Doping in CdTe: Group V in Te site

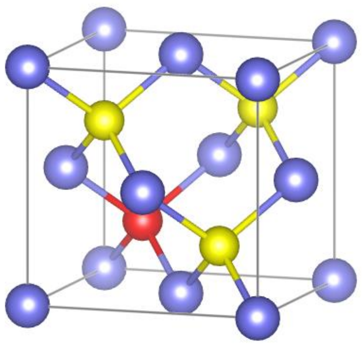
Group V



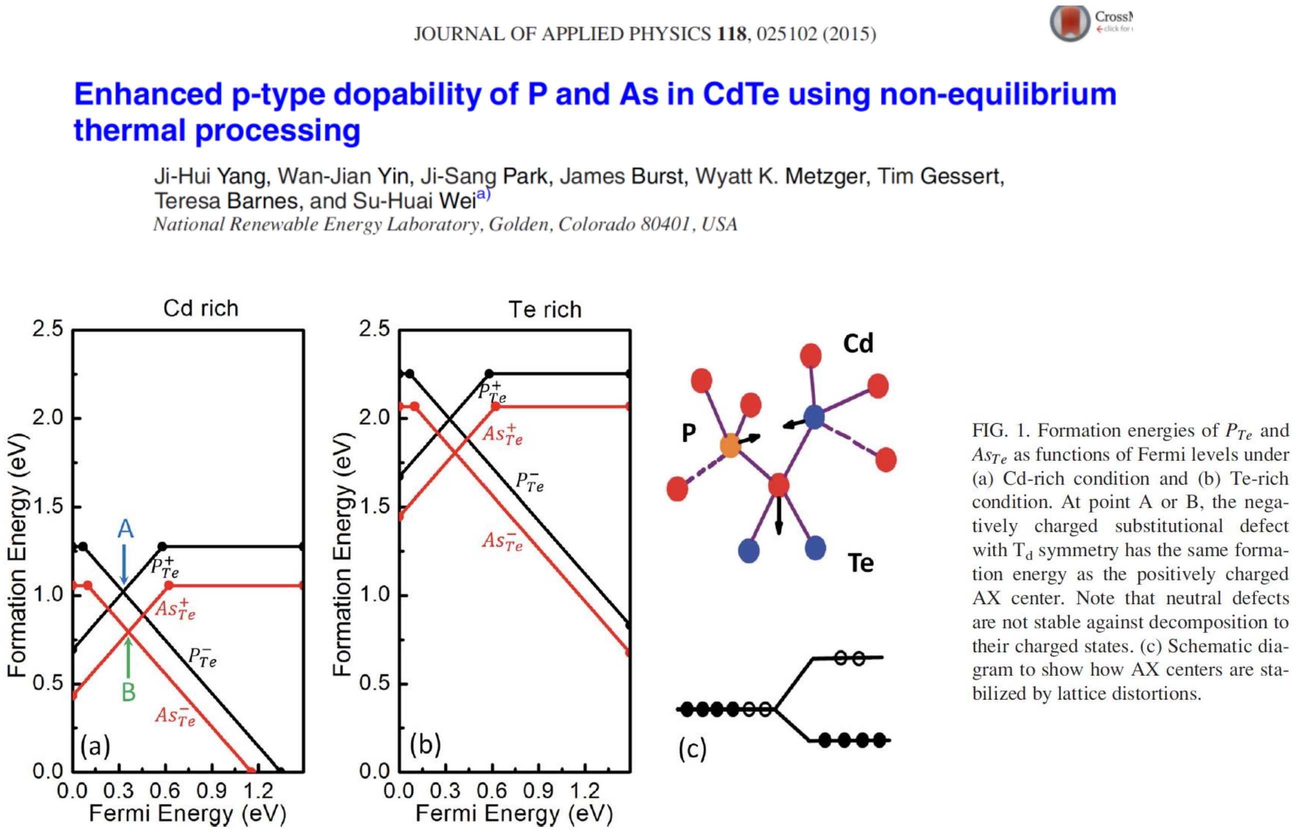
CdTe



Defect: As_{Te}



e.g., $As^{3-} + V_{Te} = (As_{Te})^{-} + h^{+}$



JOURNAL OF APPLIED PHYSICS **118**, 025102 (2015)

Enhanced p-type dopability of P and As in CdTe using non-equilibrium thermal processing

Ji-Hui Yang, Wan-Jian Yin, Ji-Sang Park, James Burst, Wyatt K. Metzger, Tim Gessert, Teresa Barnes, and Su-Huai Wei[a)]

National Renewable Energy Laboratory, Golden, Colorado 80401, USA

FIG. 1. Formation energies of P_{Te} and As_{Te} as functions of Fermi levels under (a) Cd-rich condition and (b) Te-rich condition. At point A or B, the negatively charged substitutional defect with T_d symmetry has the same formation energy as the positively charged AX center. Note that neutral defects are not stable against decomposition to their charged states. (c) Schematic diagram to show how AX centers are stabilized by lattice distortions.

Defect formation energy is based on the local chemistry environment in CdTe

Approaches to Do Group V Doping in CdTe

In situ doping

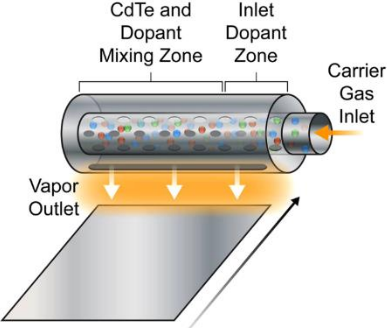
During CdTe deposition

Pros:

- **Higher dopant concentration**
- **Better control of distribution**

Cons:

- **Low activation ratio ~1%**
- **Possible dopant segregation**



VS

Ex situ doping

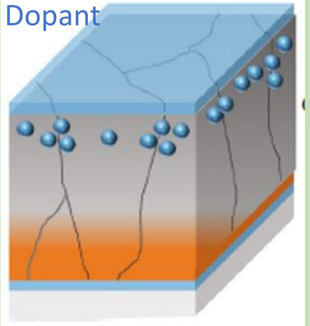
Post CdTe deposition

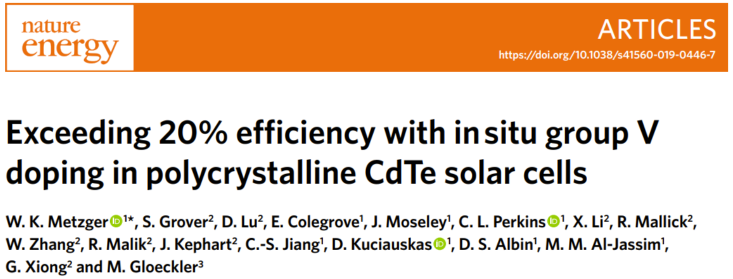
Pros:

- **Higher activation ratio ~5%**
- **Less dopant segregation**

Cons:

- **Lower dopant concentration**
- **Fixed distribution**





nature energy

ARTICLES

https://doi.org/10.1038/s41560-019-0446-7

Exceeding 20% efficiency with in situ group V doping in polycrystalline CdTe solar cells

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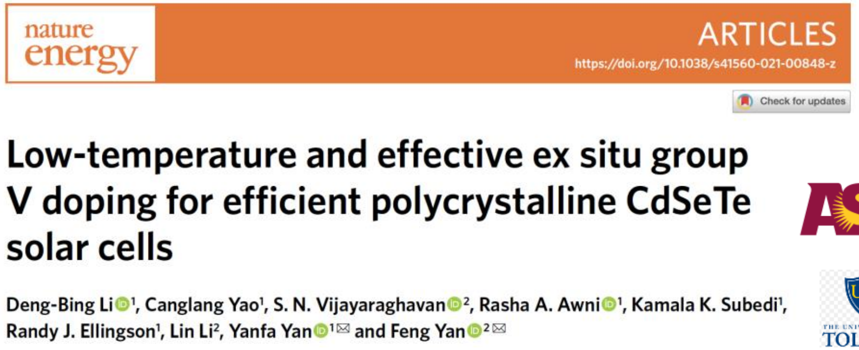
NREL Transforming ENERGY

First Solar.



nature energy

ARTICLES

https://doi.org/10.1038/s41560-021-00848-z

Check for updates

Low-temperature and effective ex situ group V doping for efficient polycrystalline CdSeTe solar cells

Deng-Bing Li[1], Canglang Yao[1], S. N. Vijayaraghavan[2], Rasha A. Awni[1], Kamala K. Subedi[1], Randy J. Ellingson[1], Lin Li[2], Yanfa Yan[1] ✉ and Feng Yan[2] ✉

ASU

THE UNIVERSITY OF TOLEDO

Ex-situ Group V Doped CdTe Solar Cells

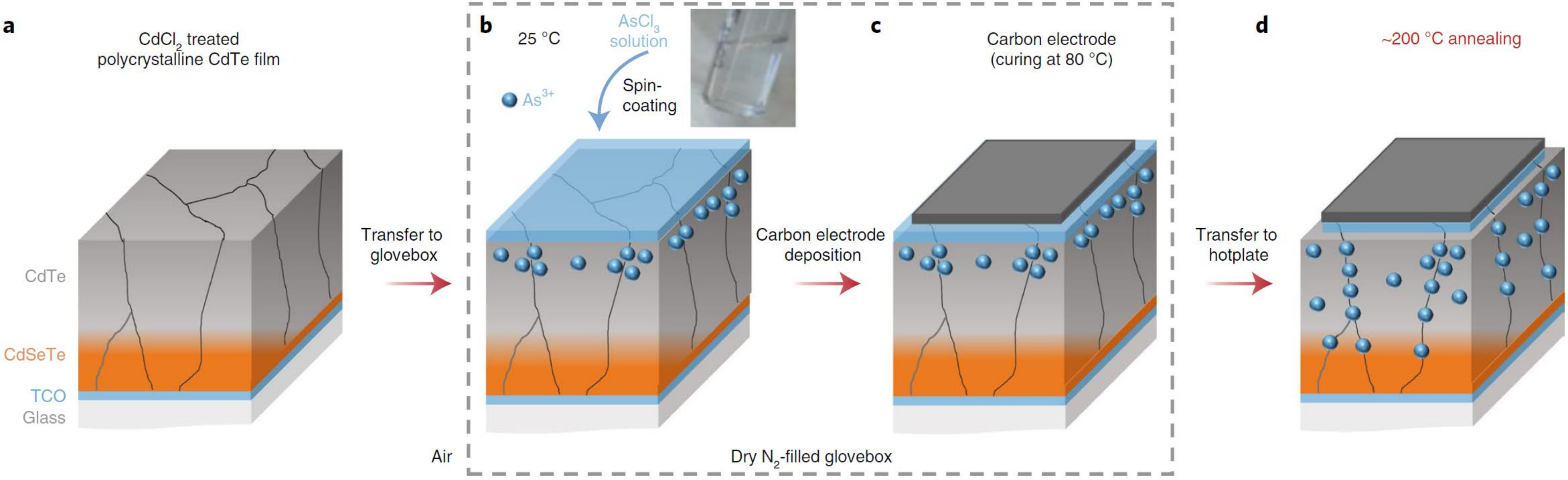
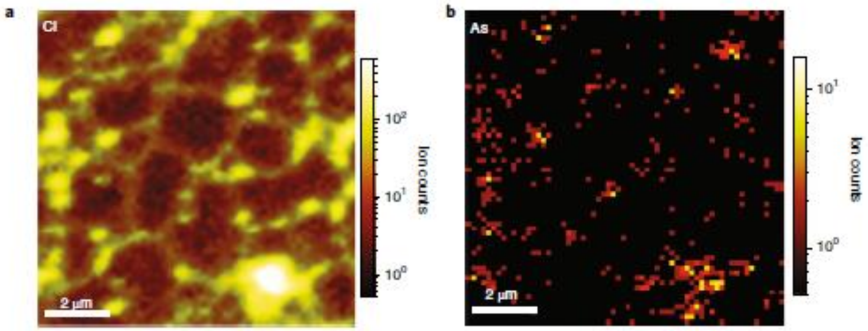
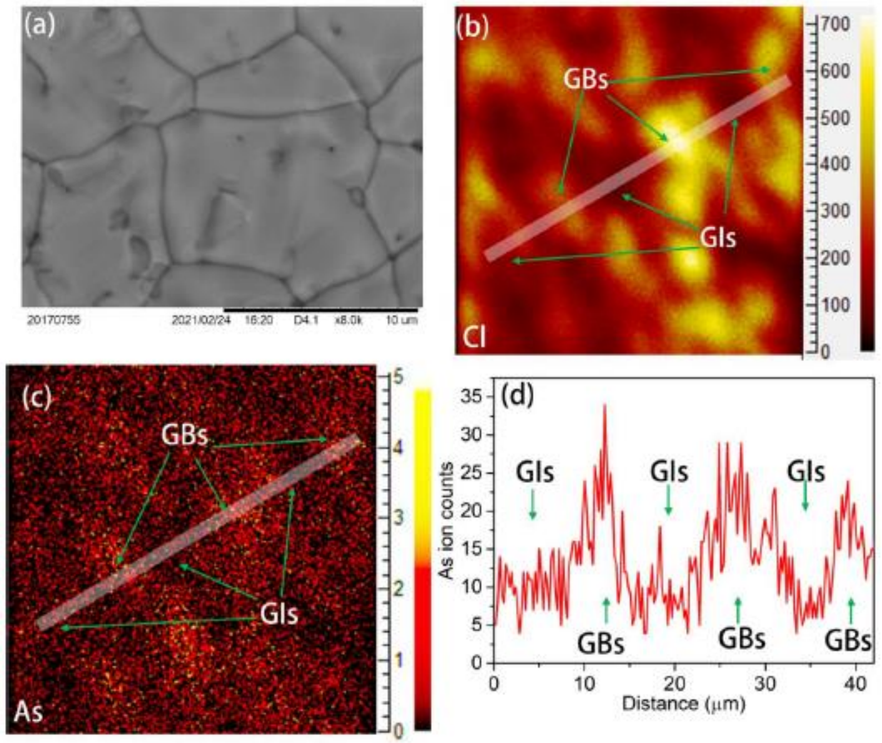


Fig. 1 | Schematic of low-temperature ex situ doping in polycrystalline CdSeTe solar cells. **a**, CdCl$_2$-treated polycrystalline CdSeTe films. **b**, Solution-processed group V deposition using the group V chlorides VCl$_3$ (that is, PCl$_3$, AsCl$_3$, SbCl$_3$ and BiCl$_3$) solution on the CdSeTe surface. Here, AsCl$_3$ was chosen as an example. A photograph of the transparent, colourless AsCl$_3$ solution is shown in the inset. All the other VCl$_3$ solutions had similar appearances. **c**, Low-temperature carbon electrode was applied to the VCl$_3$ coated CdSeTe film and was cured to dry at 80 °C. The steps shown in **b** and **c** are both processed in the dry N$_2$-filled glovebox to prevent the hydrolysis of VCl$_3$ and/or due to its toxicity. **d**, Group V diffusion into CdSeTe at low temperature (~200 °C) with carbon electrode.

Yan, etc. Nat Energy **6,** 715–722 (2021)

As Dopants Distribution in CdTe: Nanoscale





First, As ions diffuse along the grain boundaries (GBs)

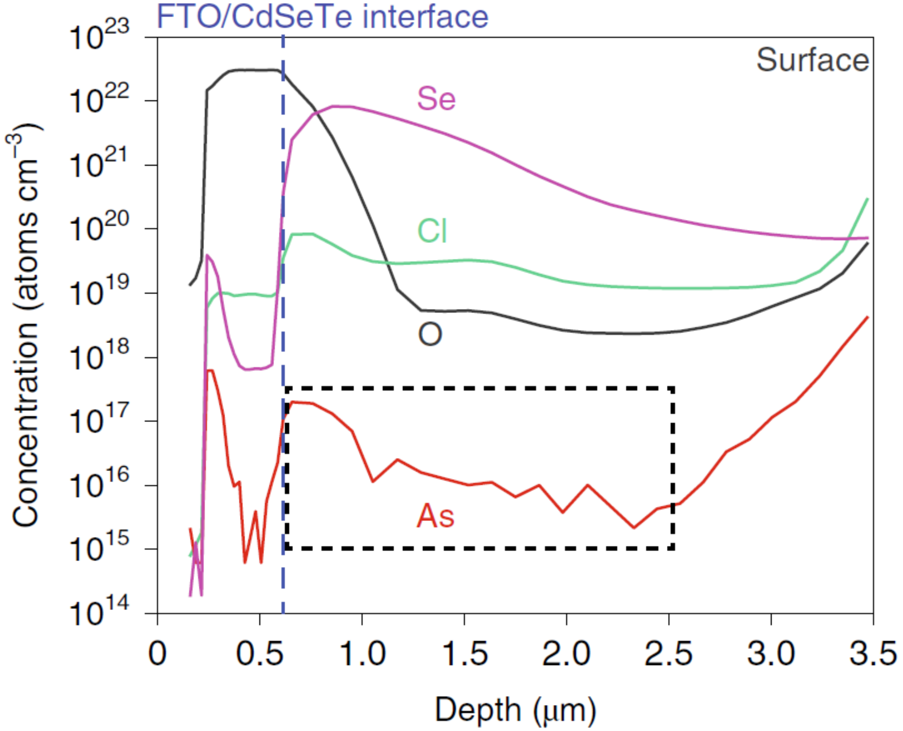
Then, As ions diffuse from GBs to grain interiors (GIs)

Second ion mass spectroscopy (SIMS) Mapping

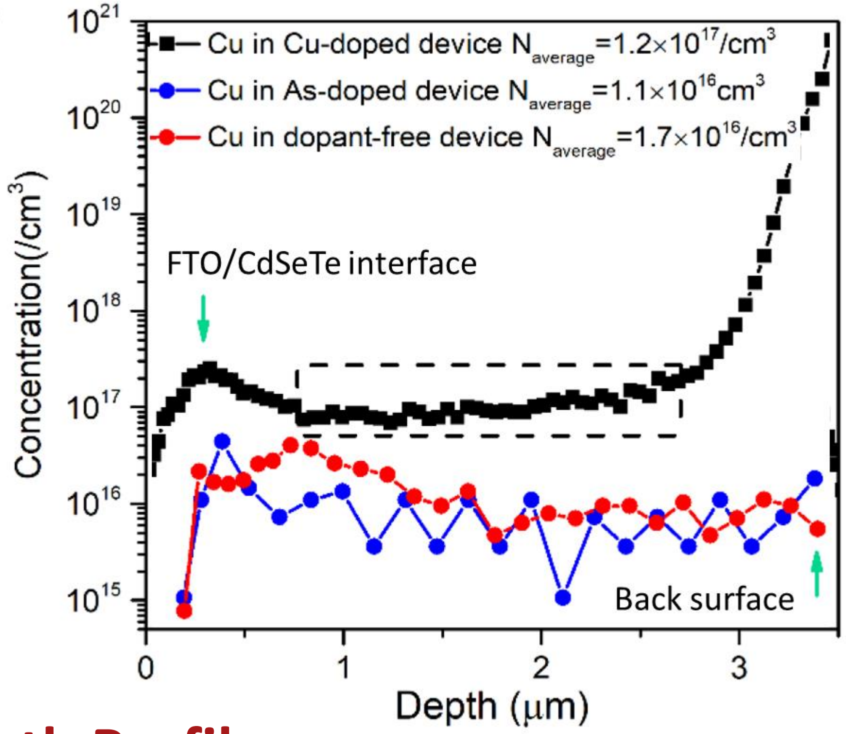
Yan, etc. Nat Energy **6,** 715–722 (2021)

As Doping Depth Profile: Macroscale

As in Te site



Cu in Cd site

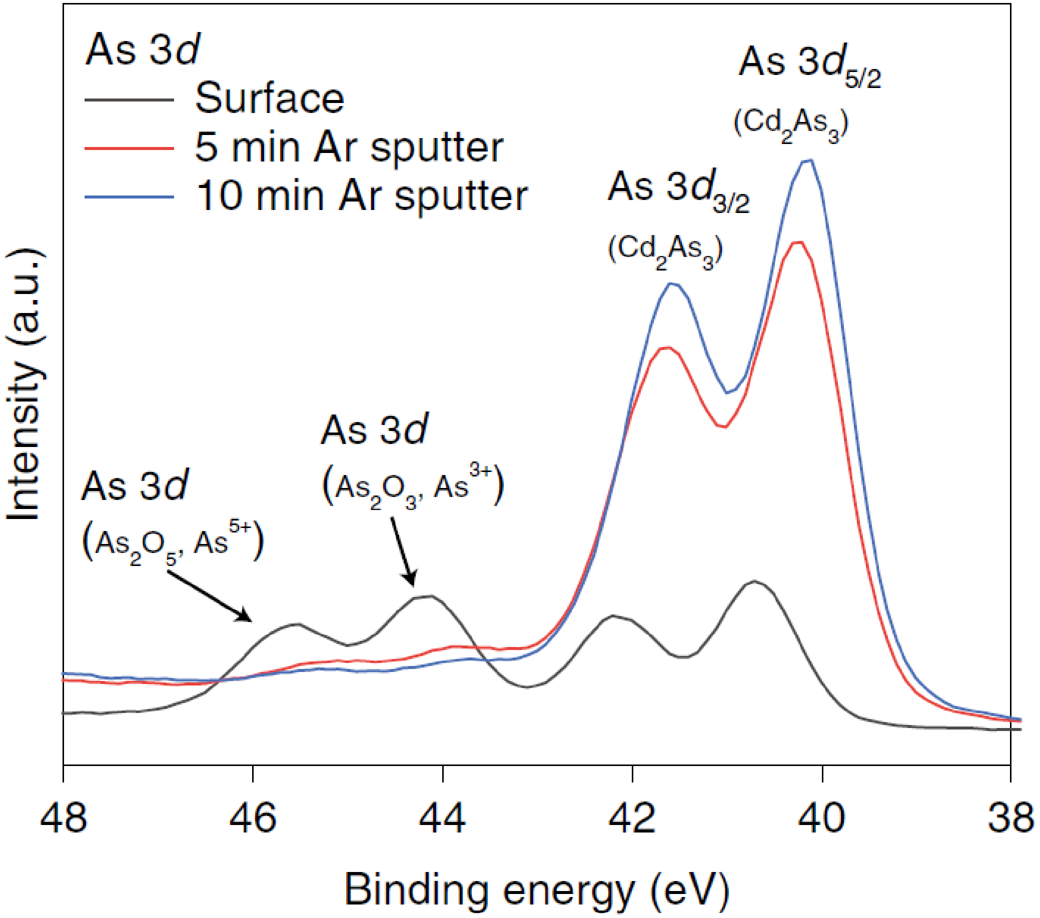


SIMS Depth Profile:

- As diffused from back side to the front end, similar to the Cu doping
- Desired doping depth profile was achieved at the back surface.

Yan, etc. Nat Energy **6,** 715–722 (2021)

As Chemical States in the CdTe

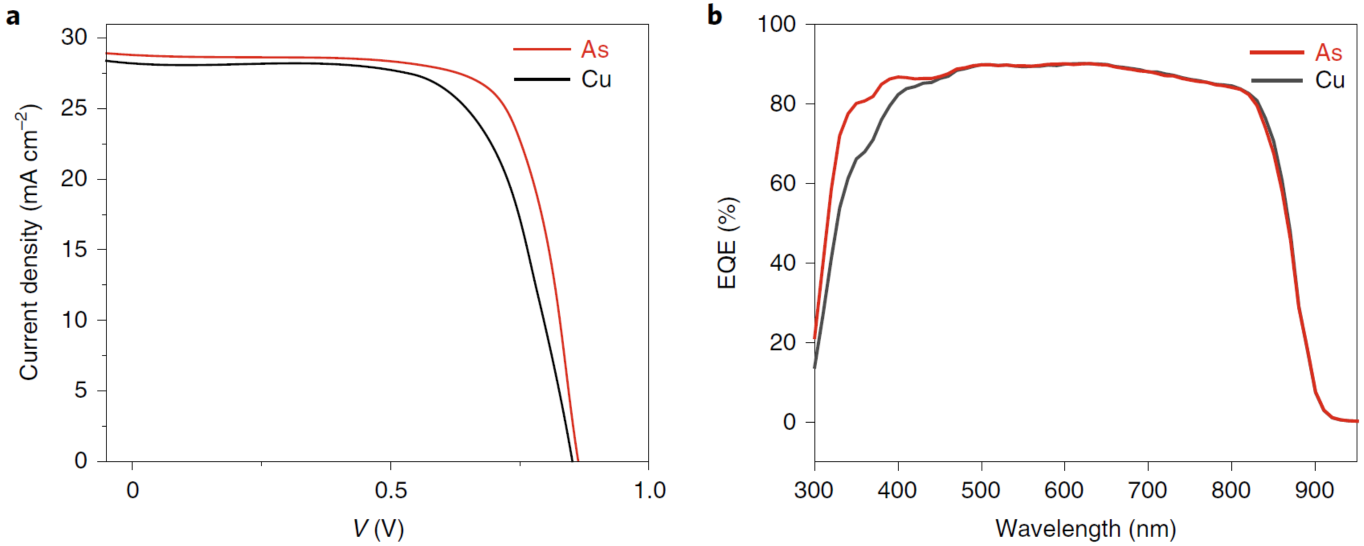


X-ray photoelectron spectroscopy (XPS) suggests Potential Doping Redox:

$$xAs^{3+}Cl_3 + Cd^{2+}Te^{2-} + 2e^- = Cd(As^{3-}{}_xTe^{2-}{}_{1-x}) + xTe^{2+}Cl_2$$

Yan, etc. Nat Energy **6,** 715–722 (2021)

As doped CdTe Device Performance



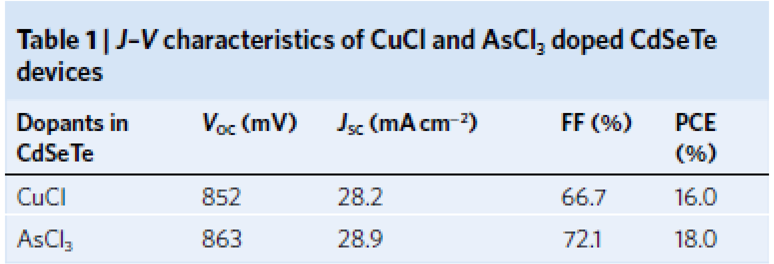
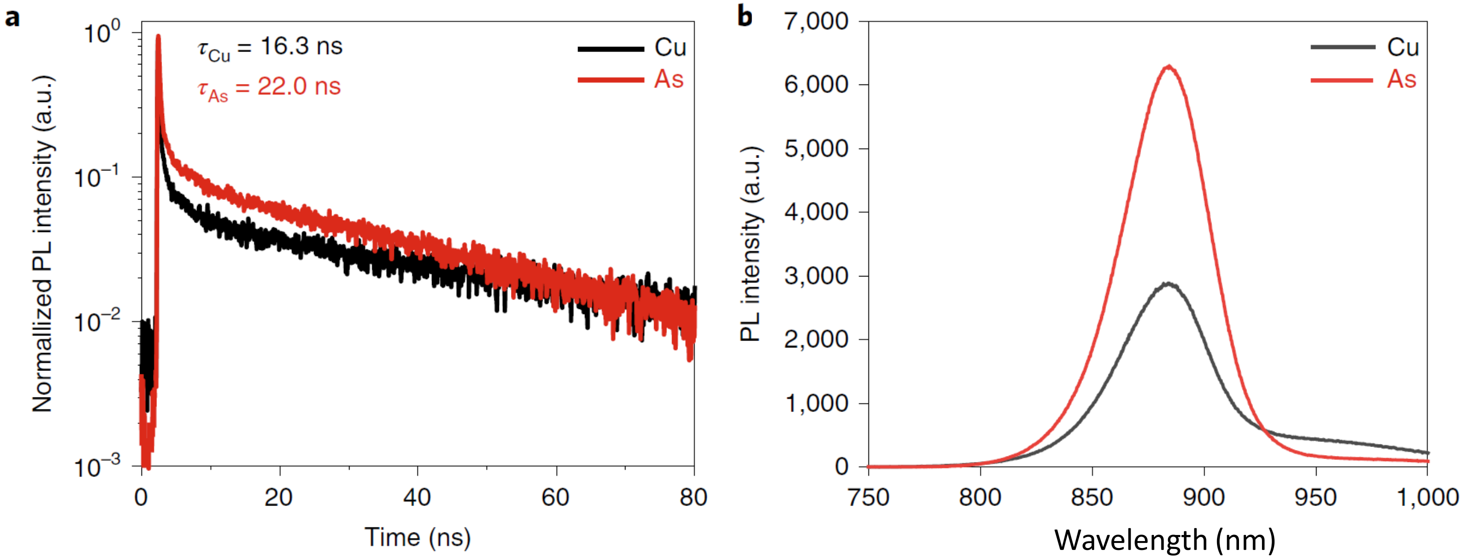


Table 1 | *J–V* characteristics of CuCl and $AsCl_3$ doped CdSeTe devices

Dopants in CdSeTe	V_{oc} (mV)	J_{sc} (mA cm^{-2})	FF (%)	PCE (%)
CuCl	852	28.2	66.7	16.0
$AsCl_3$	863	28.9	72.1	18.0

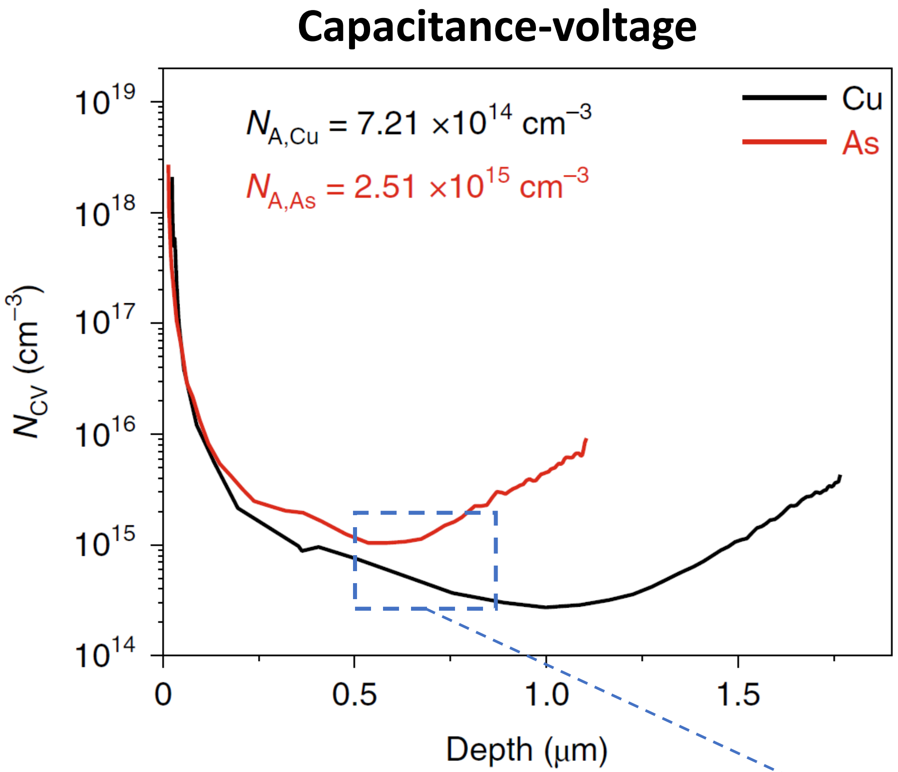


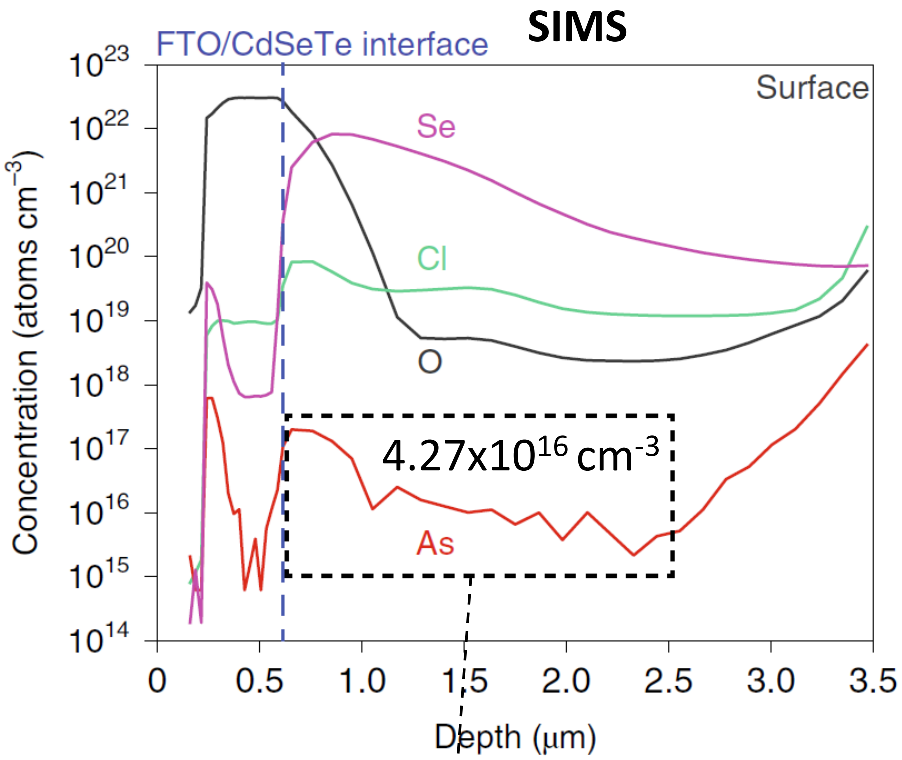
- $AsCl_3$ Improved Voc to ~863mV vs. 852 mV of CuCl solution doped process.

- **Carrier lifetime ~22 ns.**

Yan, etc. Nat Energy **6,** 715–722 (2021)

As doped CdTe : Dopant Activation Ratio

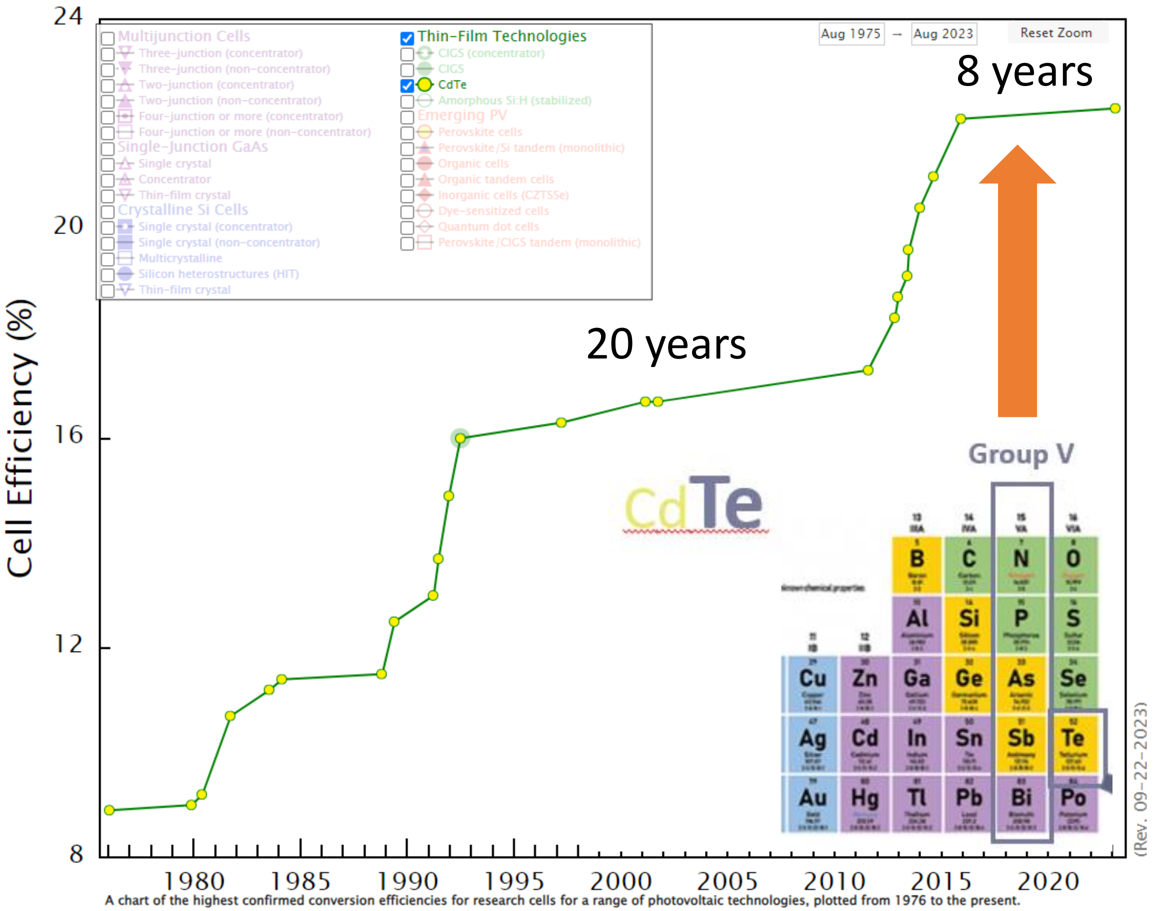

Capacitance-voltage


SIMS

Activation ratio = **Carrier concentration**/ **Incorporated dopants**

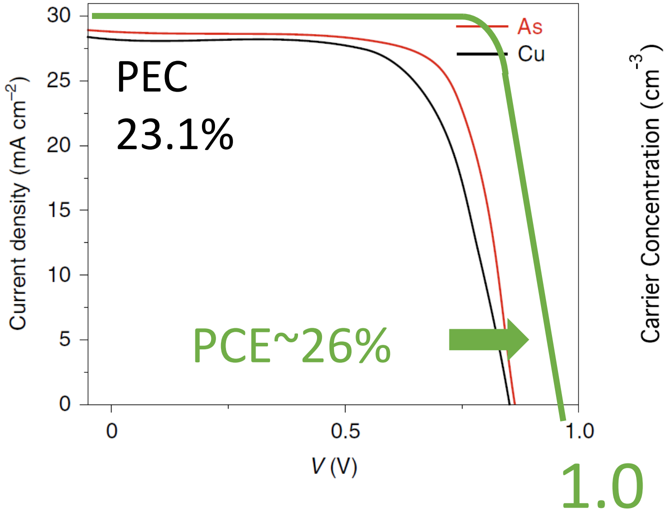
2.51×10^{15} cm^{-3}/4.27×10^{16} cm^{-3} ~ 5.88%

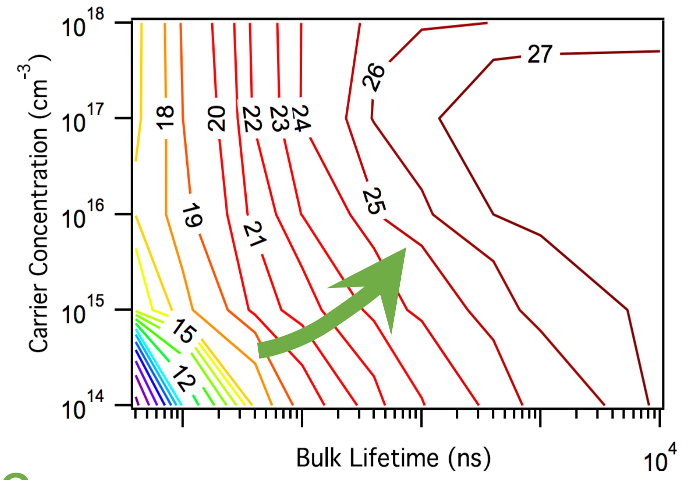
Future of CdTe Thin film Solar Cell: Efficiency



A chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present.

https://www.nrel.gov/pv/interactive-cell-efficiency.html





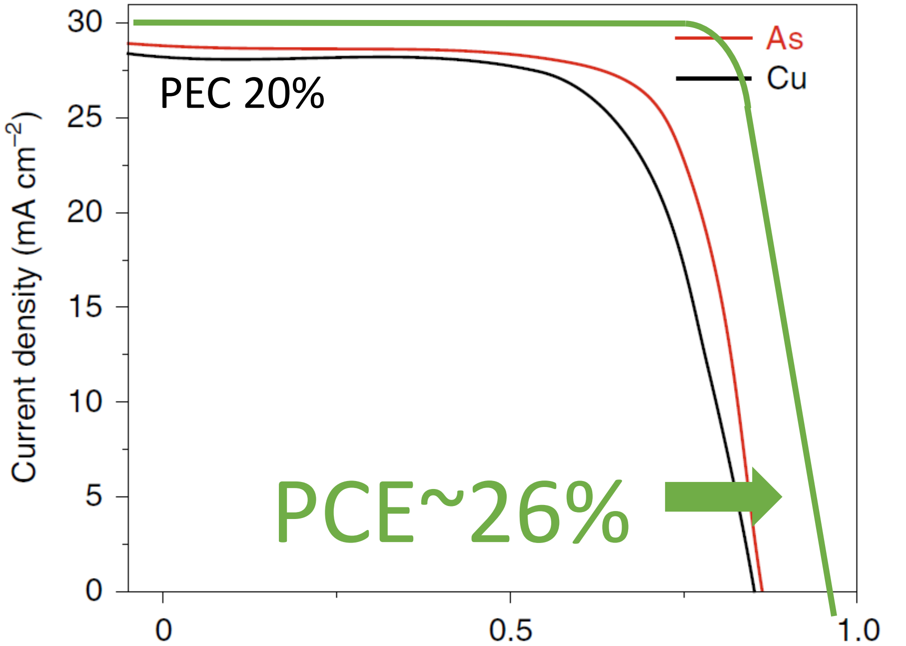
Ex-situ Bismuth Doping for Efficient CdSeTe Thin-Film Solar Cells with Open Circuit Voltages Exceeding 900 mV

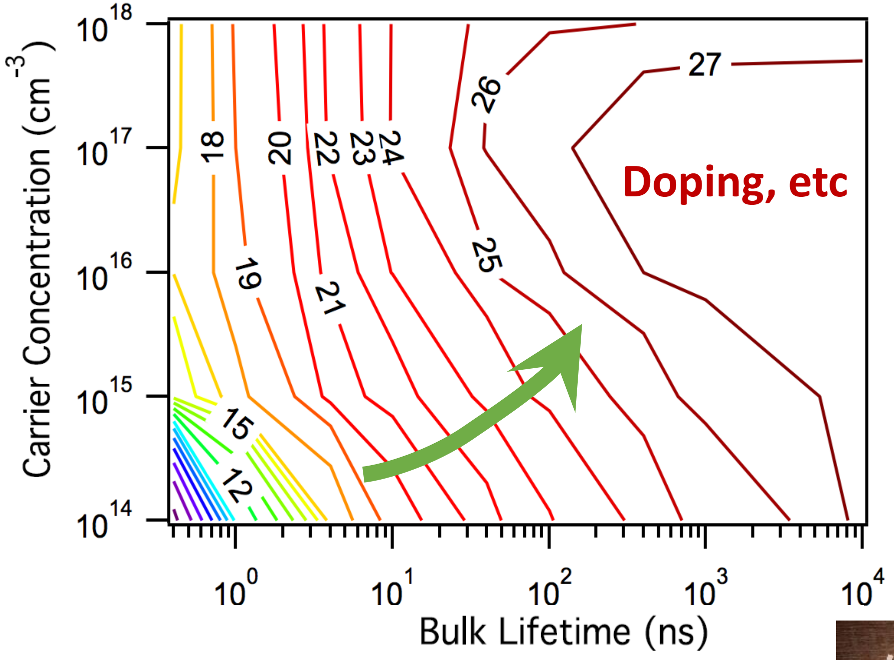
Submitted to *Joule*, In revision, 2024.

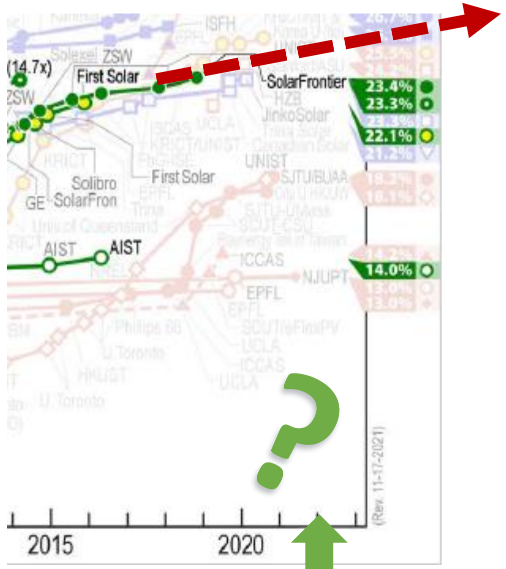
Arizona State University First Solar THE UNIVERSITY OF TOLEDO 1872 (PCE >20%)

Future of CdTe Thin film Solar Cell: Materials

Efficiency roadmap





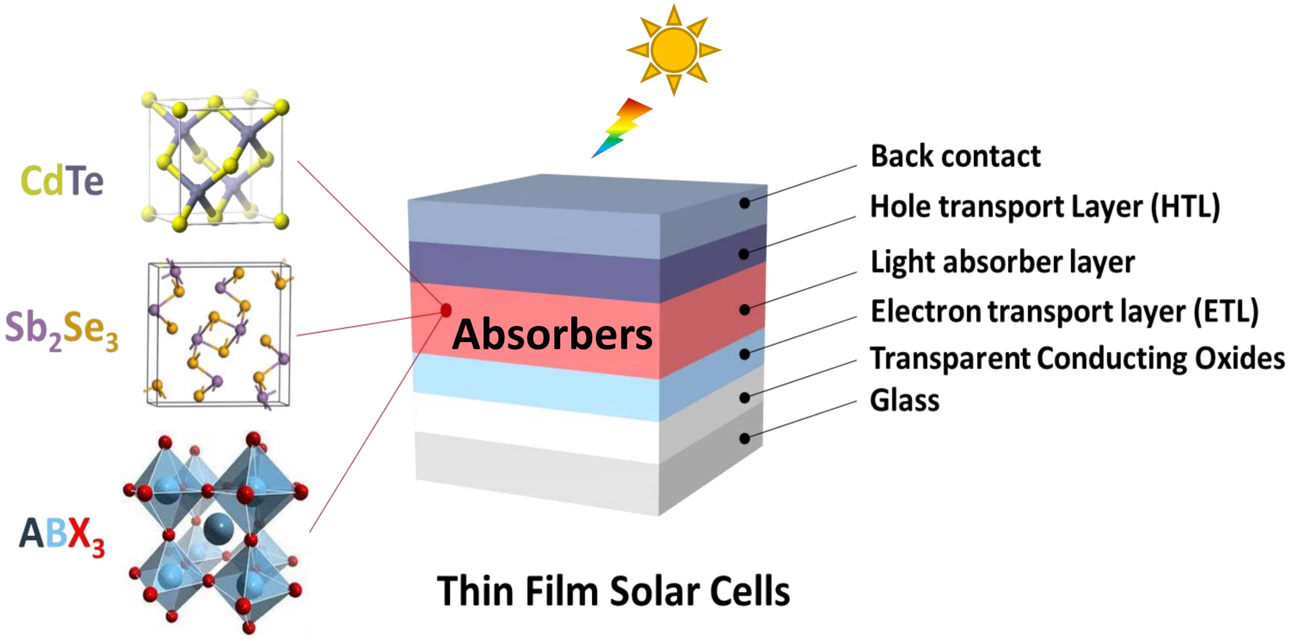


However, the **Cd toxicity** and **Te earth scarcity** **are the still the major challenges limit the CdTe technique compared to the Si solar module**
(*e.g., All the Te in the earth can be used up in 20 years*)

New **Low toxicity** and **Earth abundant** light absorbers

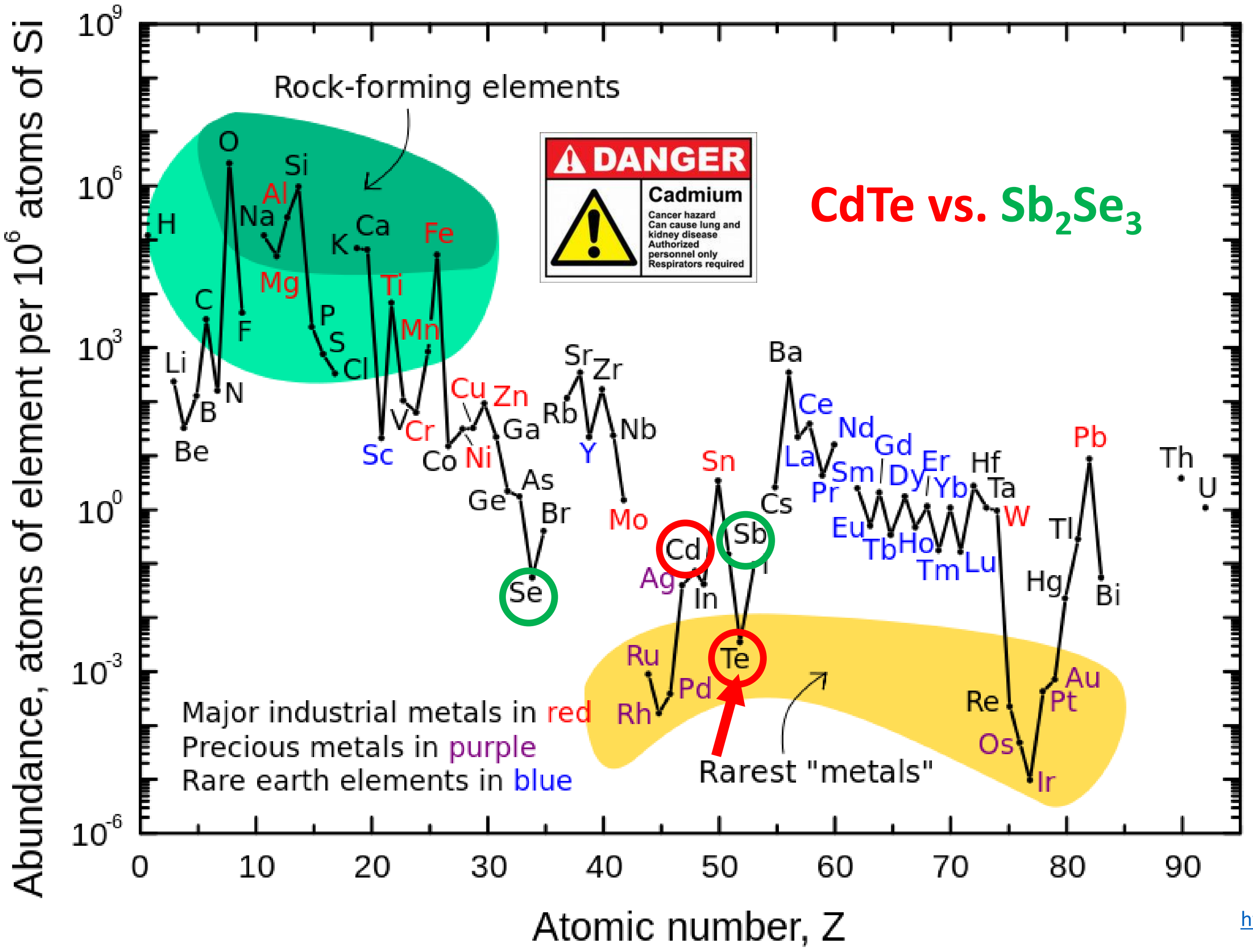
Outline

- Climate Change and Solar Energy
  - Climate Change
  - Why solar?
  - Solar cells.
- **Chalcogenides Thin Films Solar Cells**
  - CdTe Thin Film Solar Cell
    - Doping Strategy: ex-situ Group V doping
  - Sb_2Se_3 thin film solar cells
    - Close space sublimated Sb_2Se_3 solar cells.
- Carbon-based Perovskite Solar Cell
  - Stability and High Efficiency
  - Low-cost Manufacturing Approach

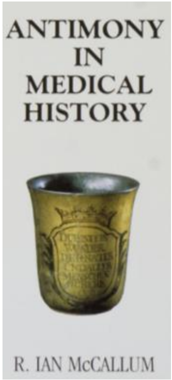


Thin Film Solar Cells

Earth Abundance and Less-toxic Sb_2Se_3



CdTe vs. Sb_2Se_3



R Ian McCallum, *Antimony in medical history: an account of the medical uses of antimony and its compounds since early times to the present*, Bishop Auckland and Edinburgh, Pentland Press, 1999, pp. xvi, 125, illus., £15.00 (1-85821-642-7).

Antimony has played a role in medicine throughout most of recorded history: the Assyrians used it to treat diseases of the urinary system, while the Ebers Papyrus (*c.* 1550 BC) advocated it as a remedy for a variety of ailments. In Europe it first gained attention through the writings of John of Rupescissa (*c.* 1300–*c.* 1365), whose *De*

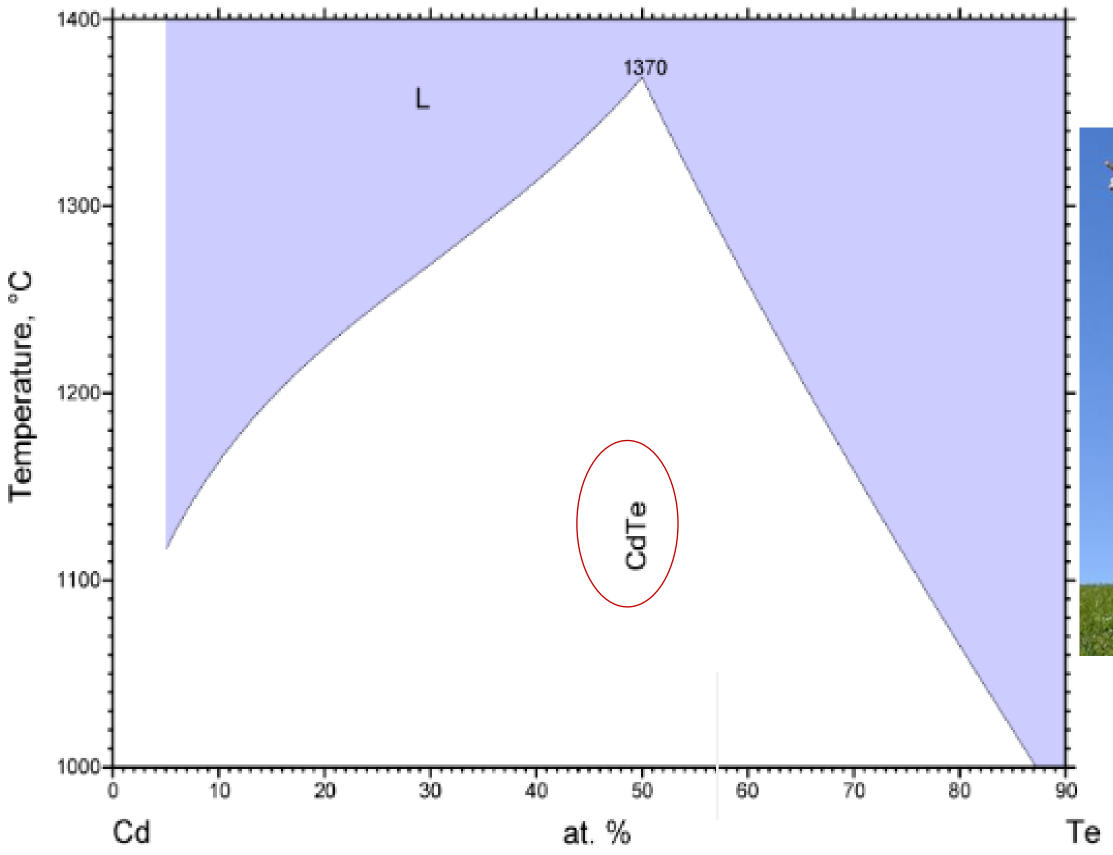
https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth's_crust#/media/File:Elemental_abundances.svg

Similarity to CdTe: Phase Diagram of Sb_2Se_3

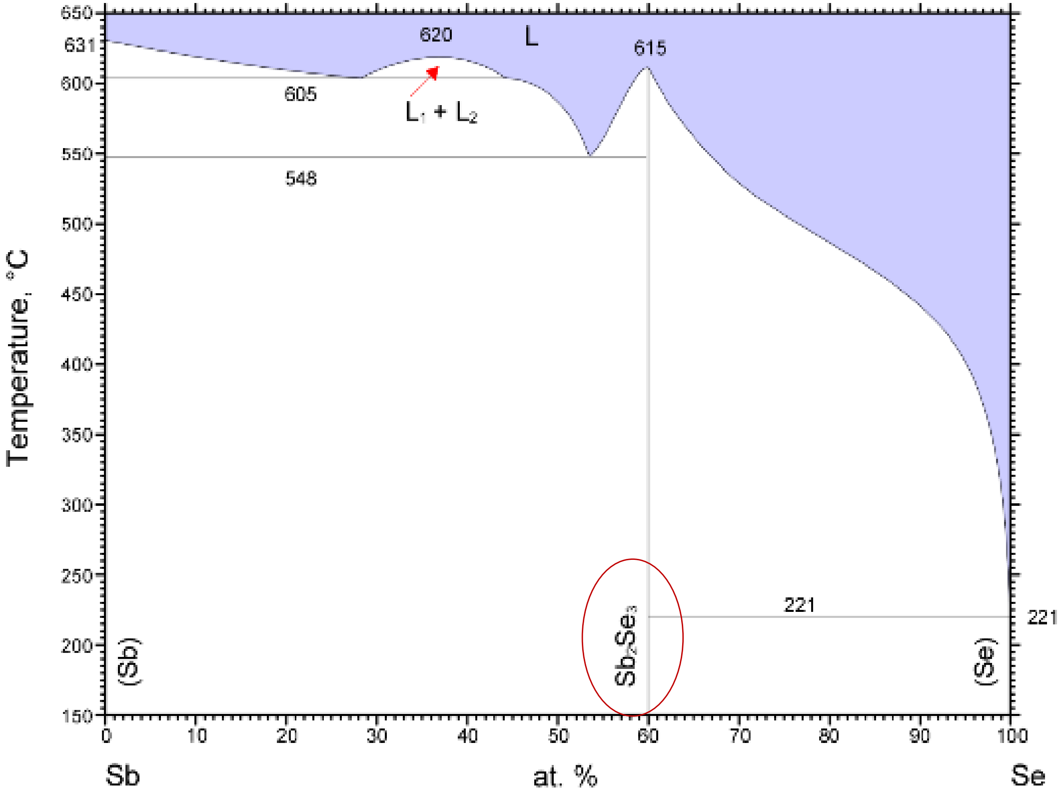
- **Phase diagram**

CdTe

Sb_2Se_3



Power of Role Model

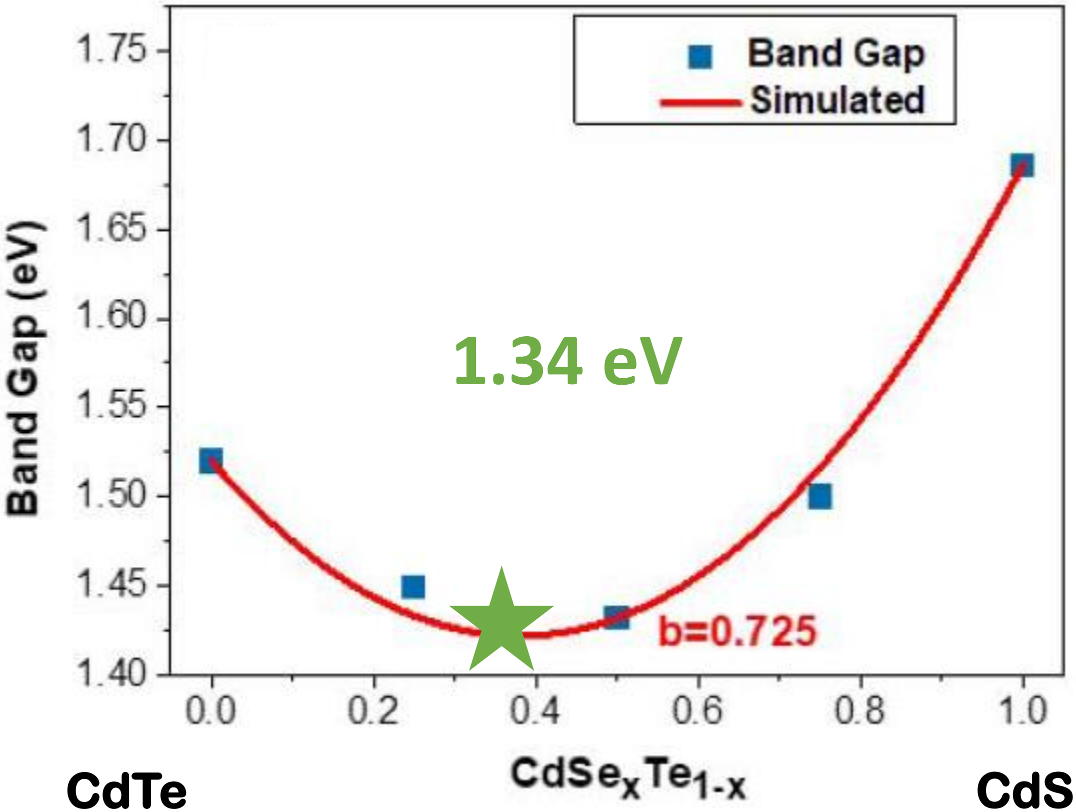


- **Both are the only stable compounds.**
- **Low energy consumption for manufacturing**

Similarity to CdTe: Tunable Bandgap of Sb_2Se_3

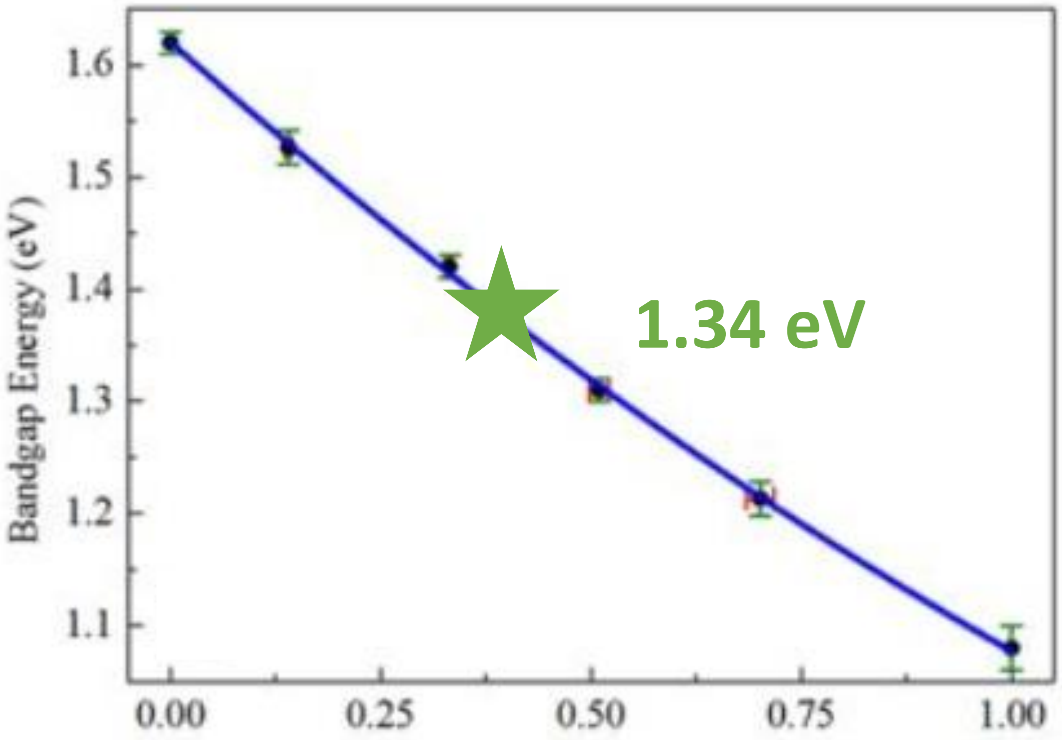
- **Tunable Bandgap via alloying/compounding**

CdTe-CdSe



CdTe **CdSe**

Sb_2Se_3-Sb_2S_3

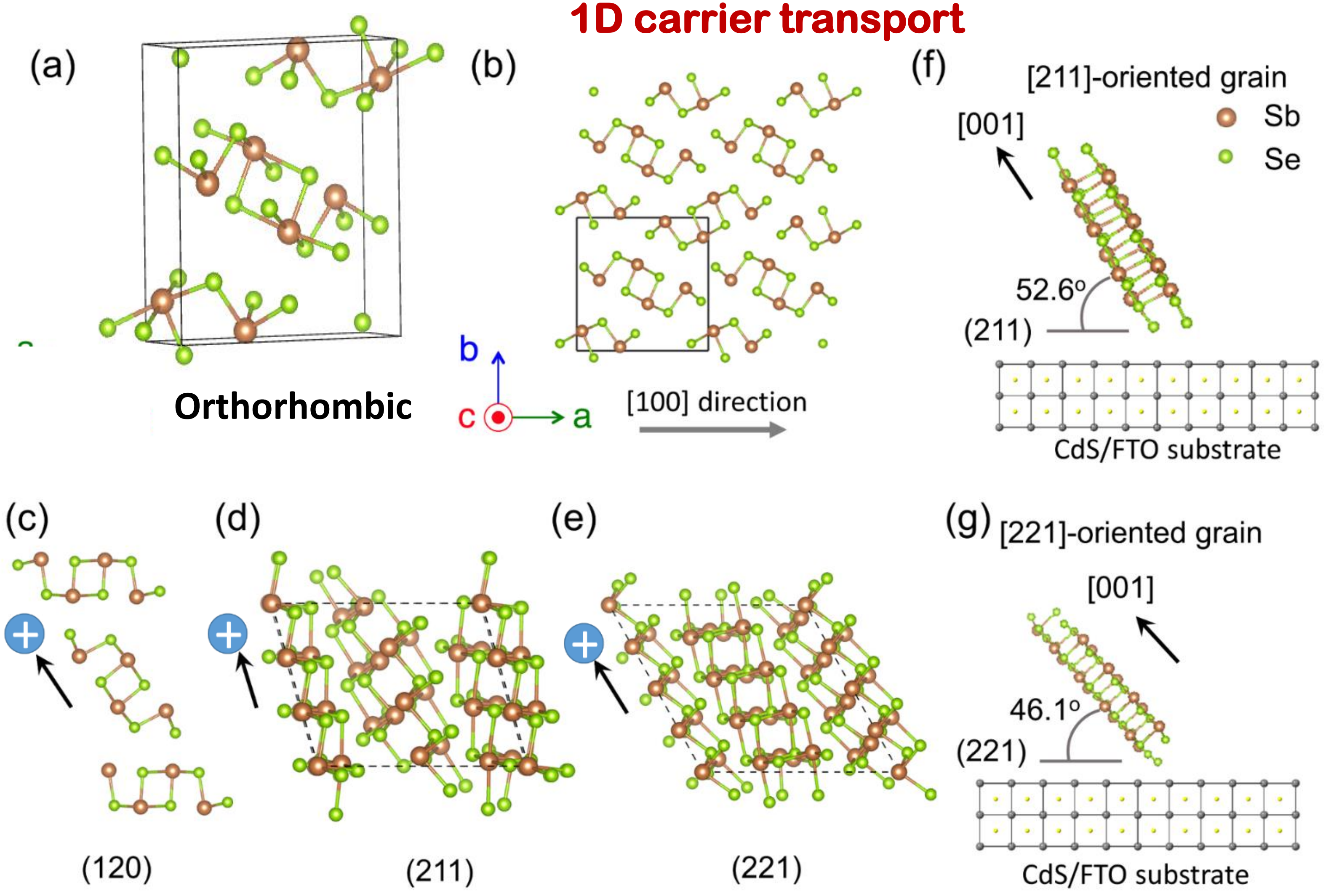


Sb_2S_3 **$Sb_2(S_{1-x}Se_x)_3$** **Sb_2Se_3**

Scientific Reports **5**, Article number: 10978 (2015)

Unique Crystal Structure of Sb_2Se_3:1D-like Structure

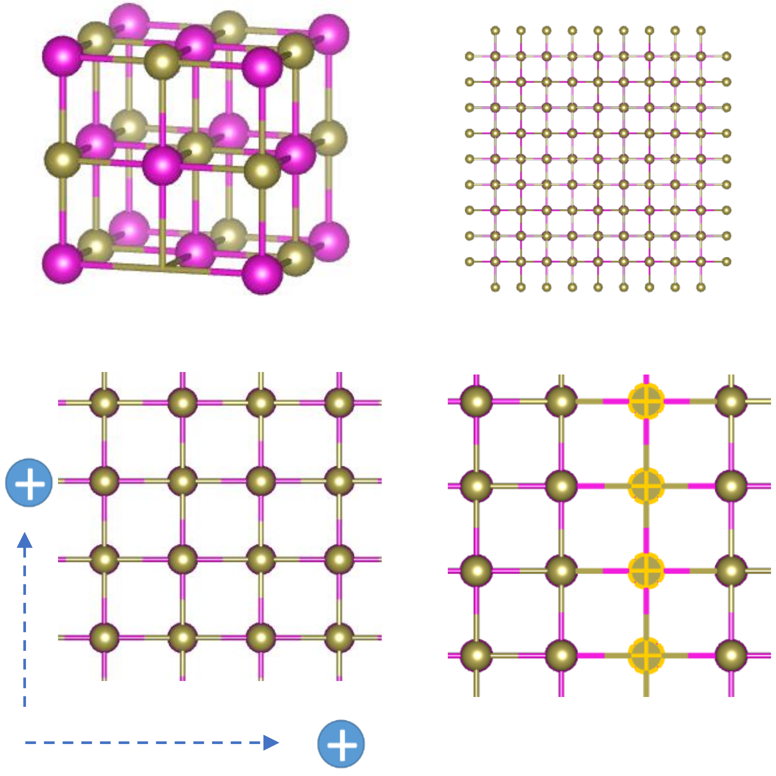
Sb_2Se_3
1D carrier transport



Orthorhombic

- **Tunable photoexcited carrier transport**

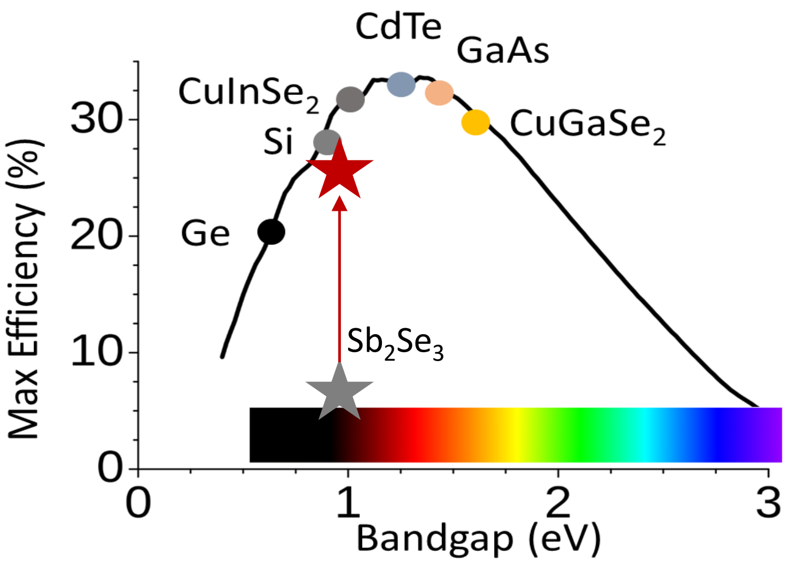
CdTe
3D carrier Transport

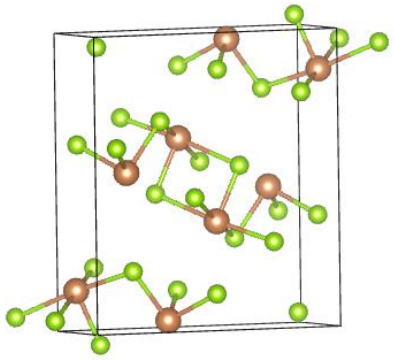


- **Isotropic growth**
- **Grain boundaries passivation needed**

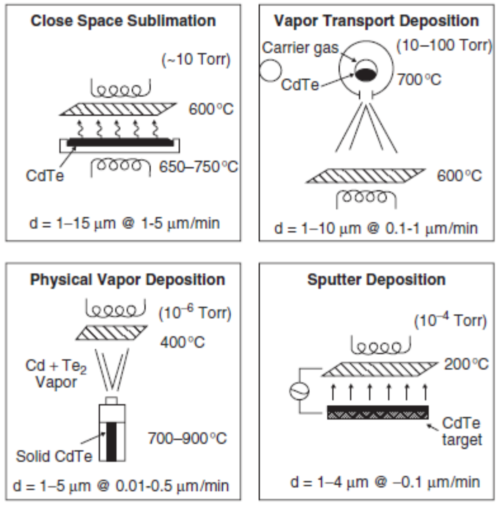
F. Yan, et al. Solar RRL 2, 1800128 (2018)

Earth Abundant Sb_2Se_3 Thin Film Solar Cells





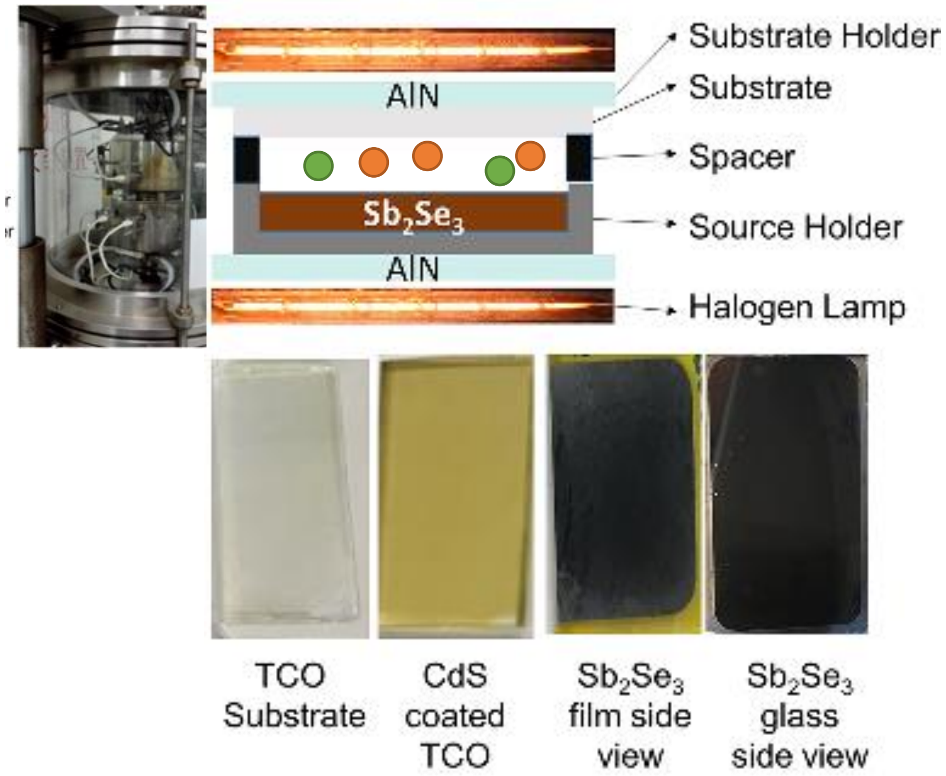
Sb_2Se_3



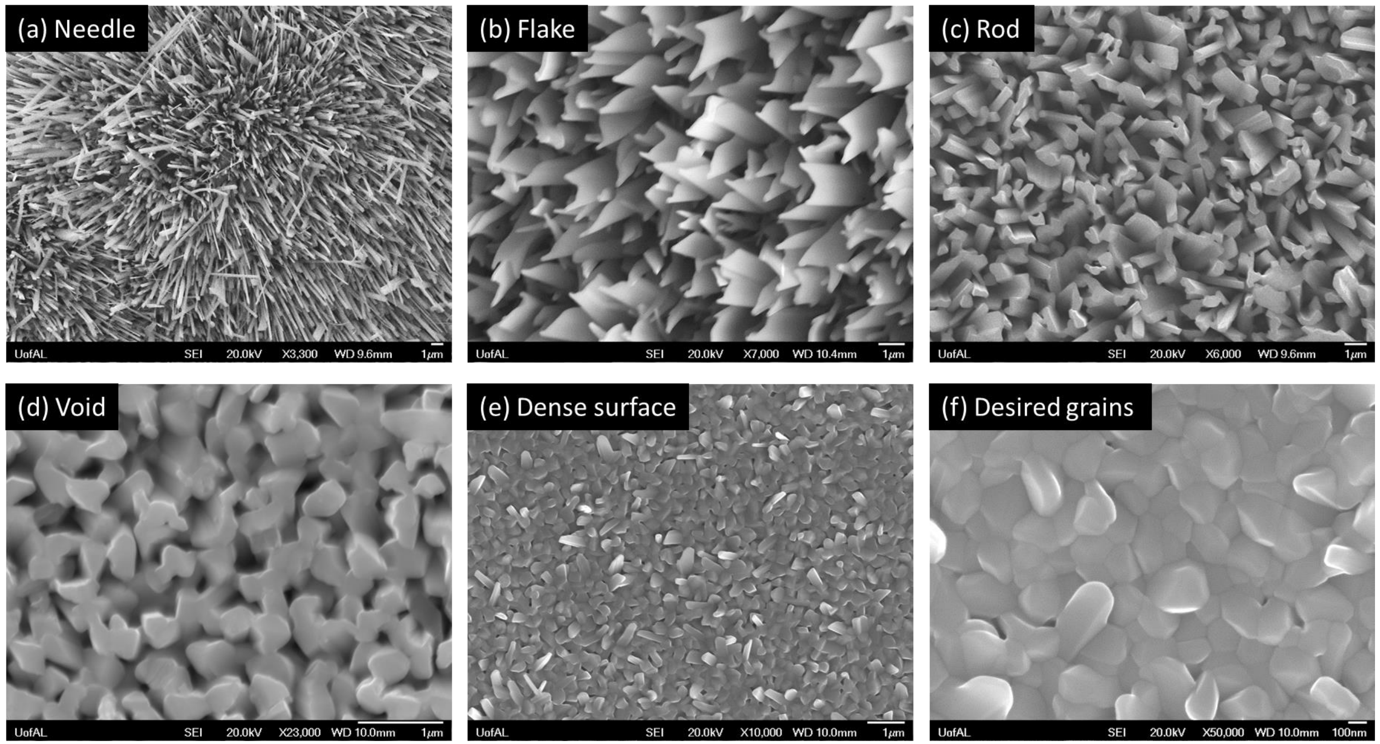
- **Nontoxic** Sb vs. toxic Cd; **Earth abundant** Se vs. Rare Te
- **Low cost** ; High efficiency (**theoretical 31% PCE)**
- **High absorption coefficient** (~10^5 cm^{-1});
- **Desired bandgap** (1.2 eV), **Intrinsic P-type semiconductor**
- **Anisotropic Orthorhombic structure with ribbons $(Sb_4Se_6)_n$**

Can we make Sb_2Se_3 solar cell like CdTe technology?

Sb_2Se_3 Thin Film Vapor Deposition Challenges



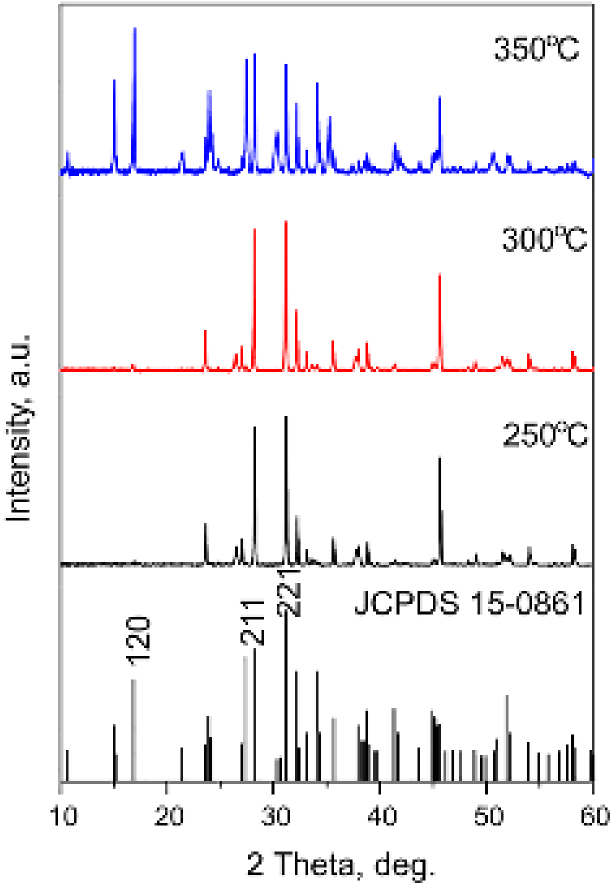
Close spaced sublimation (CSS)
(Physical Vapor Deposition)

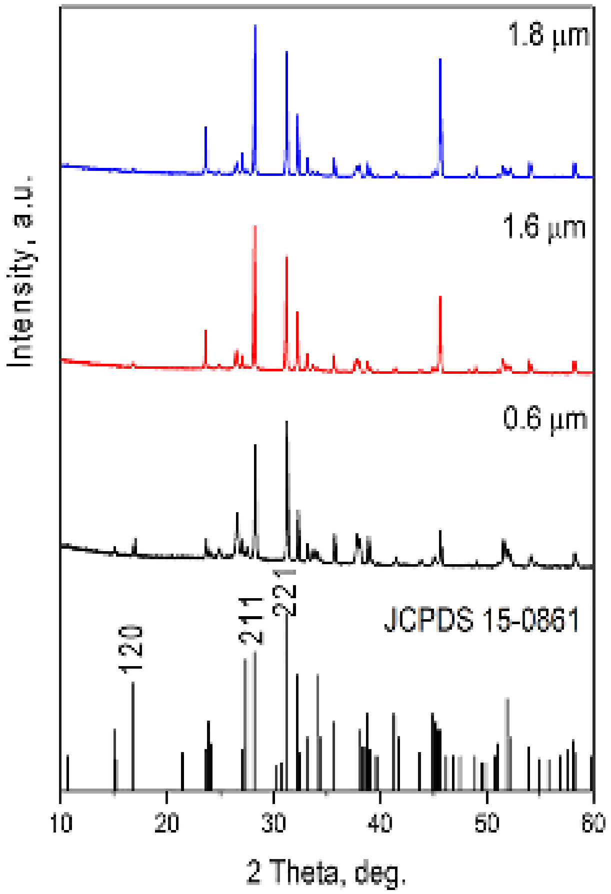


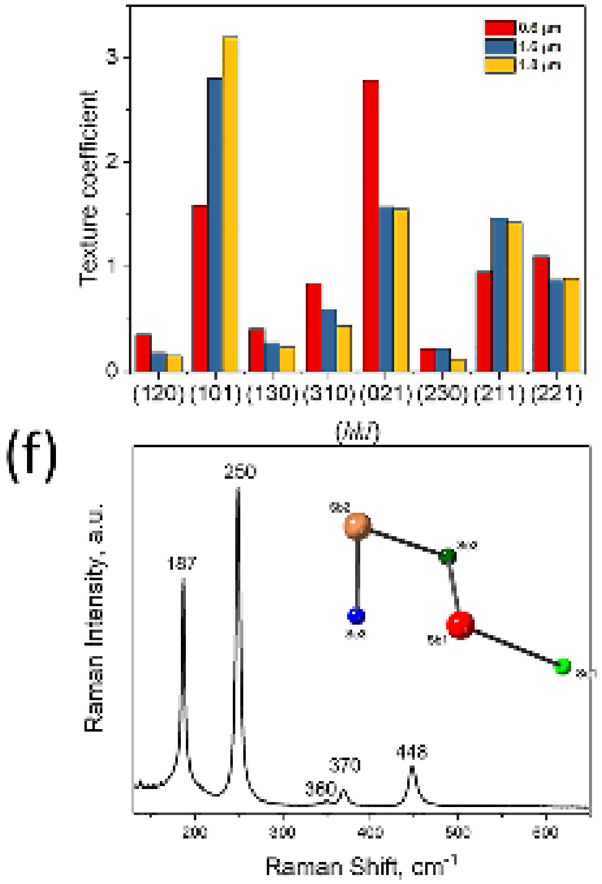
Challenges for thin film growth of Sb_2Se_3 due to its noncubic structure.

Yan, etc, Solar RRL 2, 1800128 (2018)

Tune the Sb_2Se_3 Thin Film Deposition Conditions



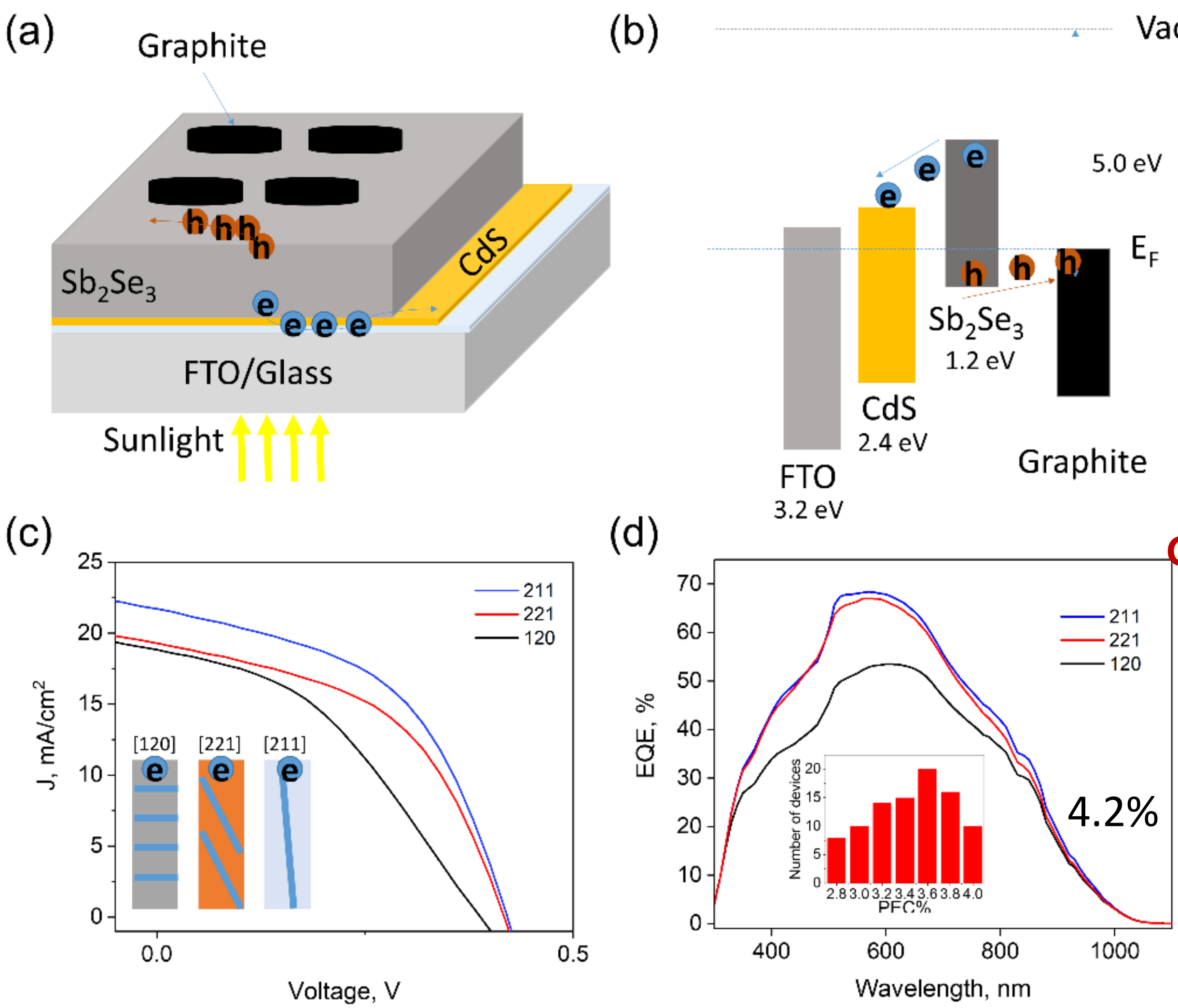




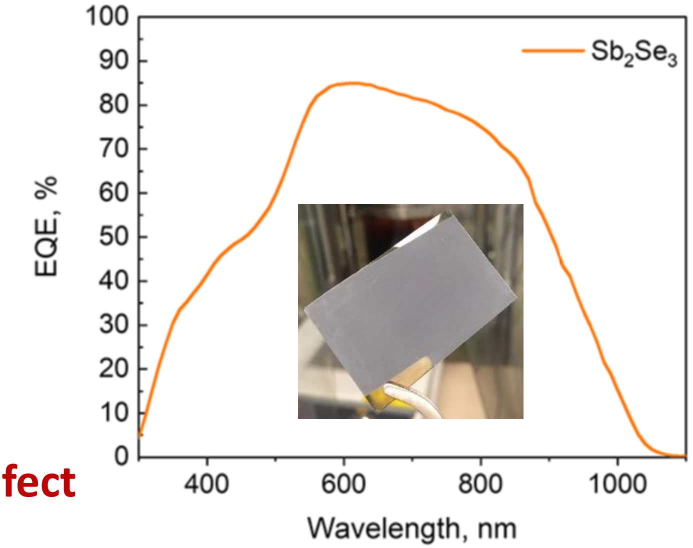
- **Substrate temperature significantly impact the 1D nanoribbons orientation**
- **Thickness sensitive to the nanoribbon's orientation**

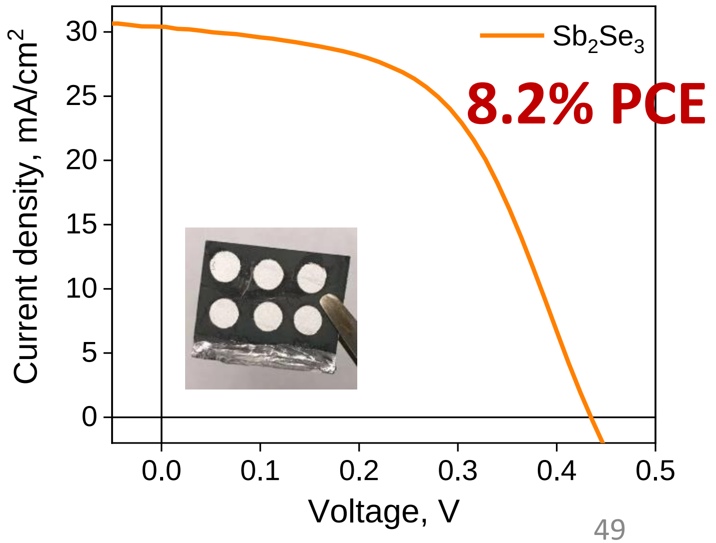
Yan, etc, Solar RRL 2, 1800128 (2018)

Sb_2Se_3 Device Performance



Growth, Interface, Defect Engineering





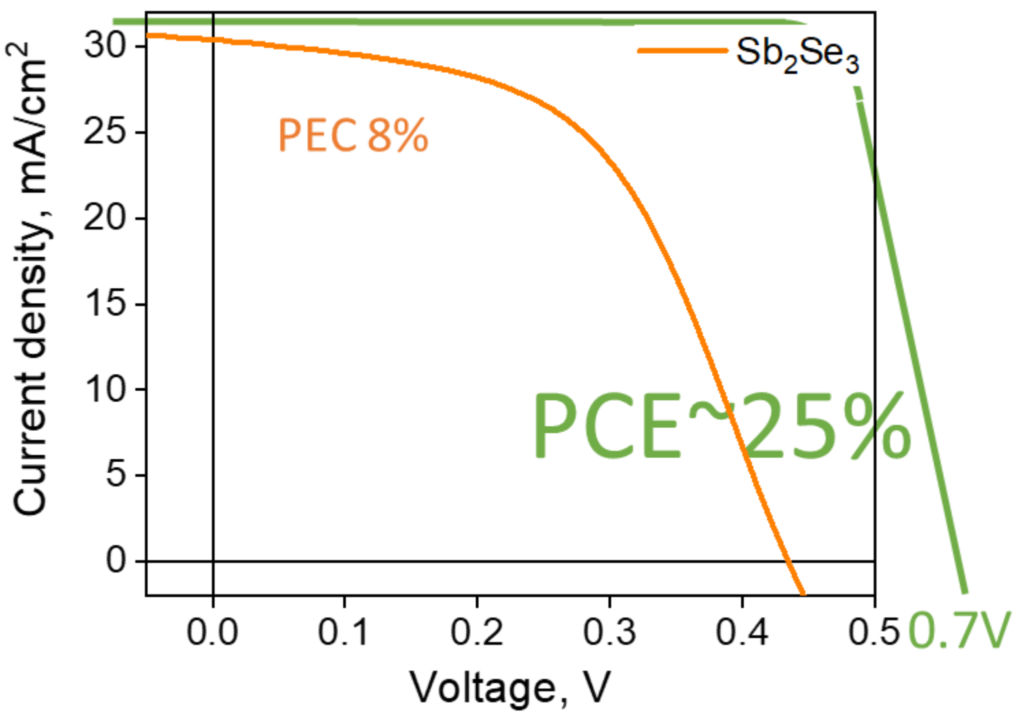
- **Ribbons dependent device performance, i.e., normal to substrate**
- **Decent efficiency, 8%, as grown without doping, and other treatment.**

F. Yan, et al. Solar RRL 2, 1800128 (2018)

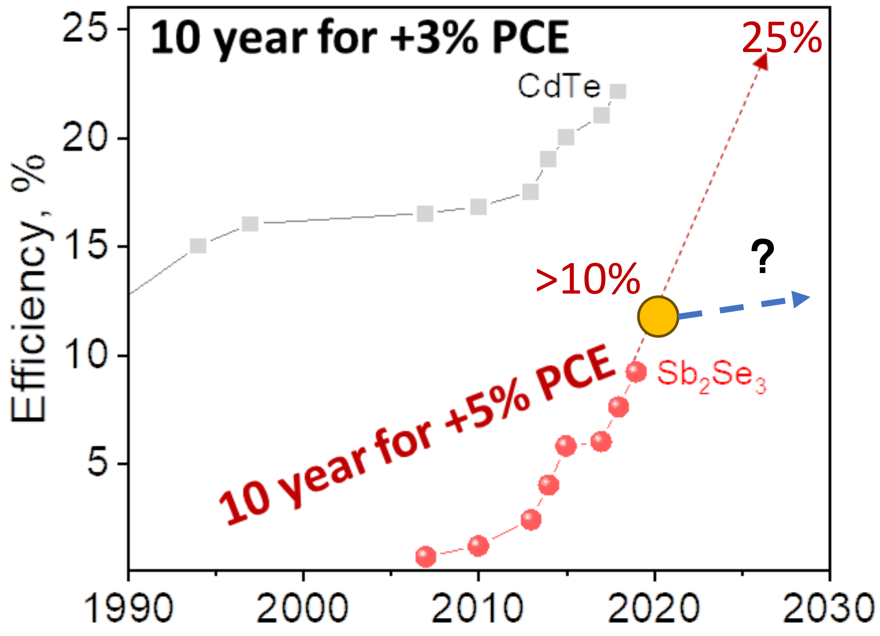
F. Yan, etc, Solar RRL, 2019, 2020, 2021, 2022, 2023, 2024

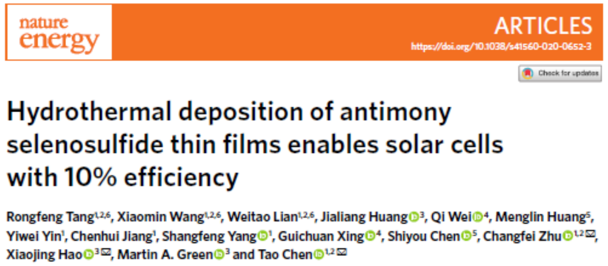
Future of Sb_2Se_3 Thin film Solar Cell

Future Efficiency roadmap ~5 to 20 years



- Materials Engineering
- Device Engineering
- Bandgap Engineering
- Defect Engineering
- New Device Architecture




nature energy

ARTICLES

https://doi.org/10.1038/s41560-020-0652-3

Hydrothermal deposition of antimony selenosulfide thin films enables solar cells with 10% efficiency

Rongfeng Tang[1,2,6], Xiaomin Wang[1,2,6], Weitao Lian[1,2,6], Jialiang Huang[3], Qi Wei[4], Menglin Huang[5], Yiwei Yin[1], Chenhui Jiang[1], Shangfeng Yang[1], Guichuan Xing[4], Shiyou Chen[5], Changfei Zhu[1,2] ✉, Xiaojing Hao[3] ✉, Martin A. Green[3] and Tao Chen[1,2] ✉

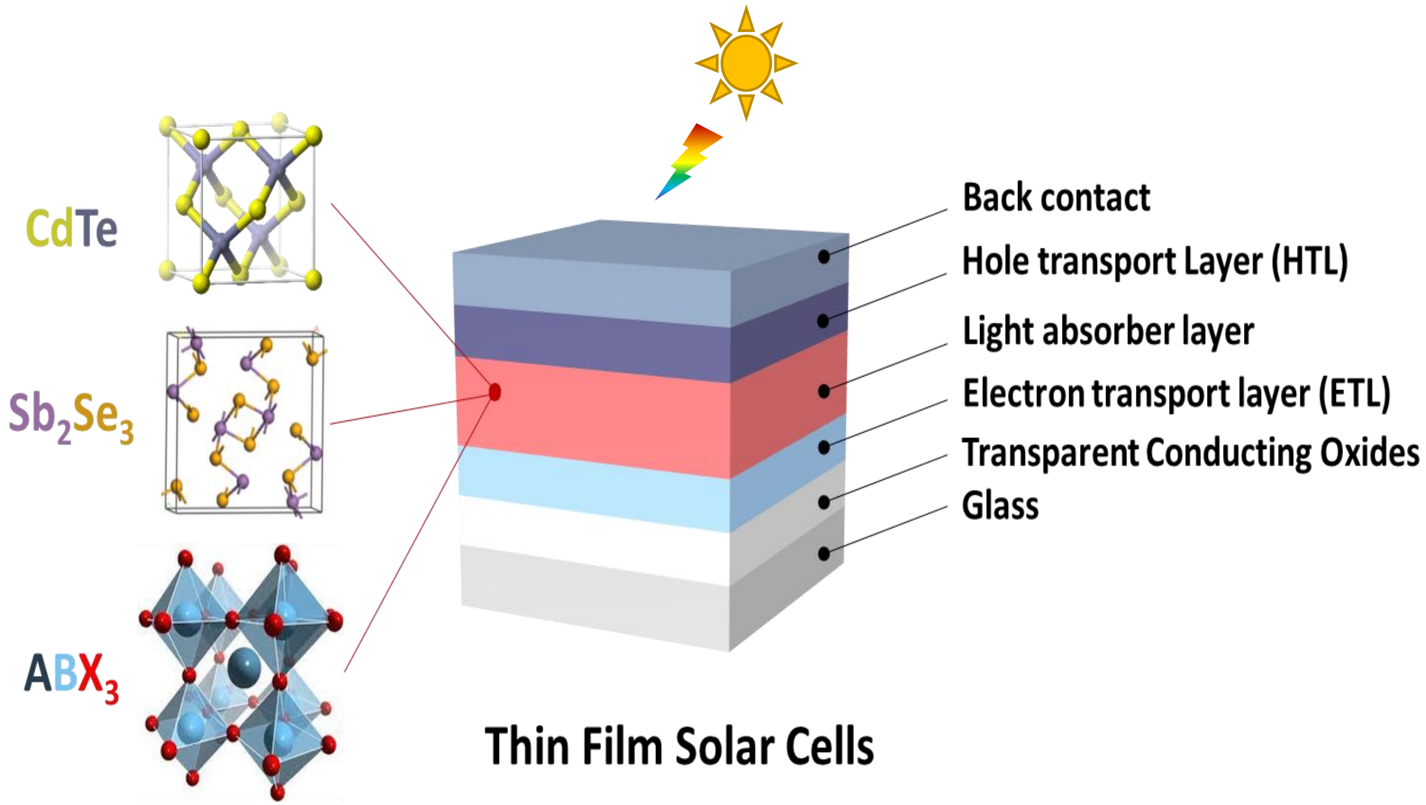
New technologies to improve the Solar Cell Device Performance?

Defects control for the V_{Se}, V_{Sb}, and antisites

Adv. Mater. **2022**, *34*, 2202969
Joule 8, 2105–2122, July 17, 2024

Outline

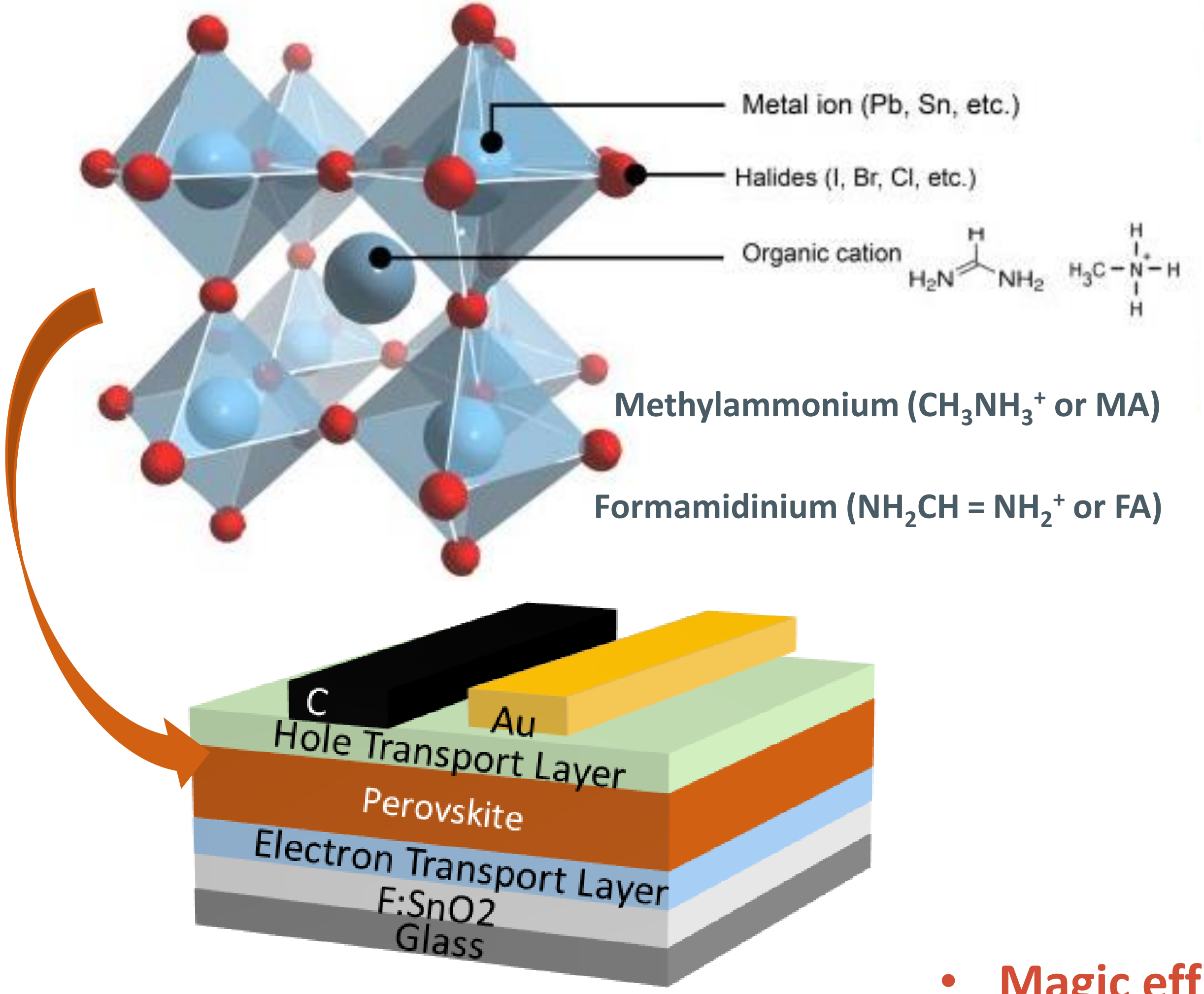
- Climate Change, EV and Solar Energy
  - Climate Change & EV
  - Why solar?
  - Solar cells.
- Chalcogenides Thin Films Solar Cells
  - CdTe Thin Film Solar Cell
    - Doping Strategy: ex-situ Group V doping
  - Sb_2Se_3 thin film solar cells
    - Earth Abundant Low Toxic Alternative of CdTe
    - Guided Carrier Transport in Noncubic Structure.
- **Carbon-based Perovskite Solar Cell**
  - **Marriage of Stability and High Efficiency**
  - **Low-cost Manufacturing Approach**



Thin Film Solar Cells

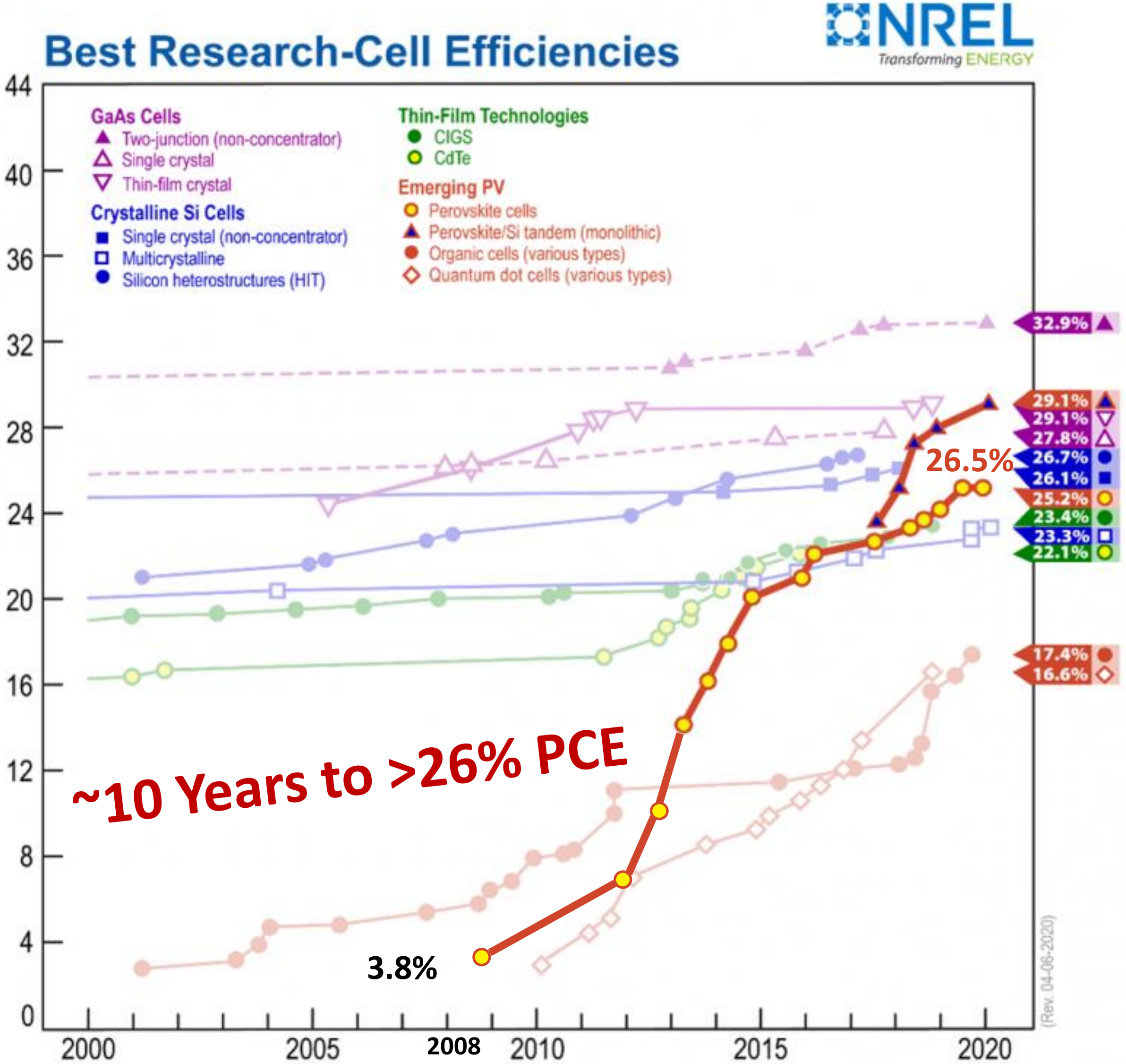
Perovskite Thin Film Solar Cells

Organic-Inorganic Hybrid Perovskite Structure



Methylammonium ($CH_3NH_3^+$ or MA)

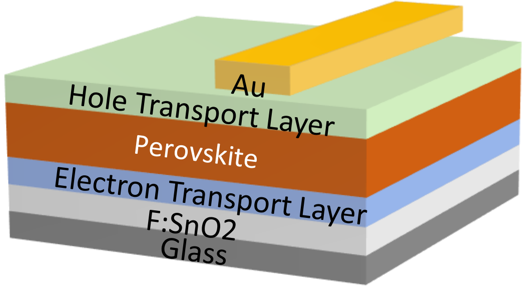
Formamidinium ($NH_2CH = NH_2^+$ or FA)



- Magic efficiency improvement from 3% to 26% in 10 years.

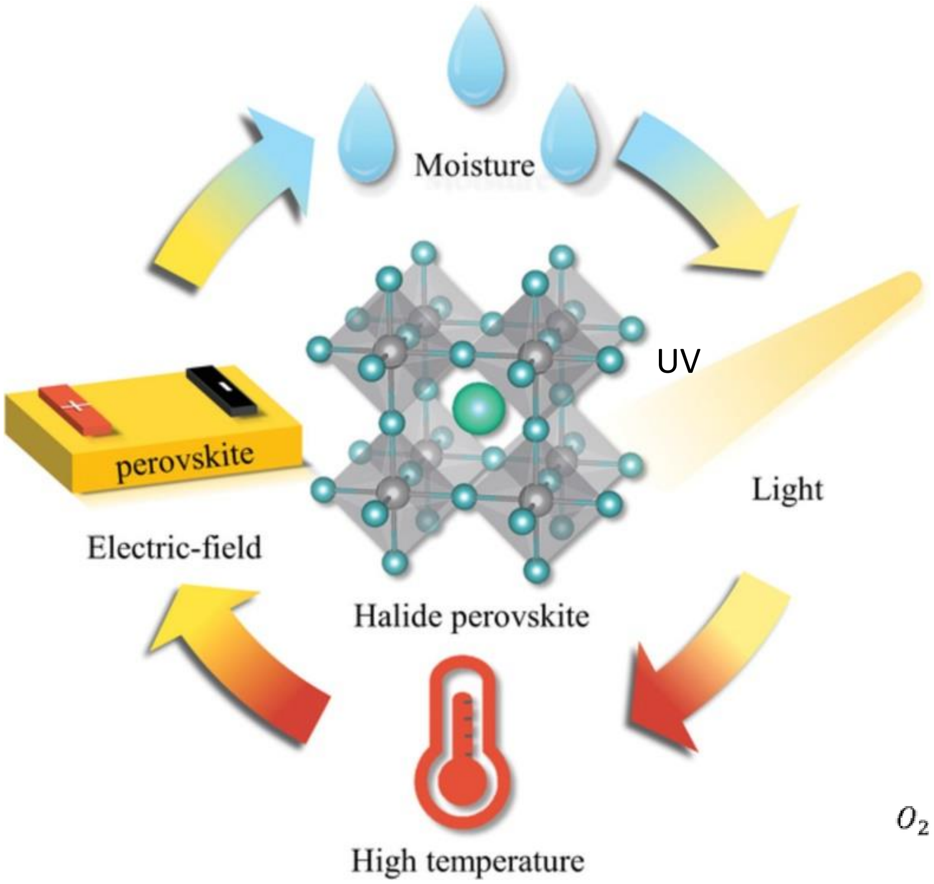
Sourece: https://research.csiro.au/printedpv/perovskite/

Metal-Electrode Based Perovskite Solar Cells

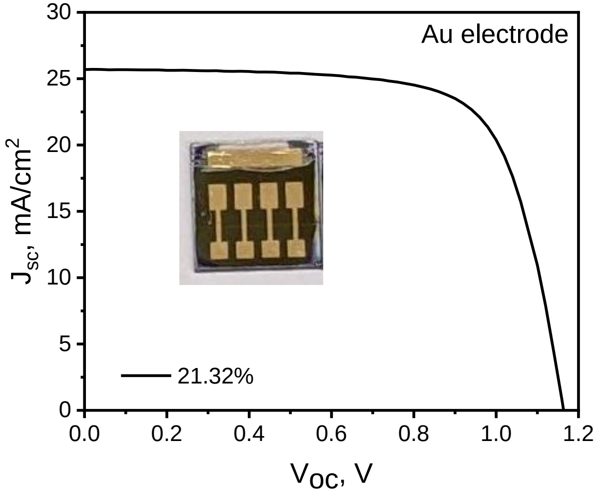


Organic-Inorganic Perovskite solar cell Issues:

- ***Ambient instability*** (i..e, *Heat, Moisture, UV light, Oxygen sensitivity*)
- ***High-cost manufacturing*** (e.g, .Noble Au electrode~$60/g, and organic hole transport layer)



InfoMat. 2020; 2: 1034



$CH_3NH_3PbI_3 \xleftrightarrow{H_2O} CH_3NH_3PbI + PbI_2$

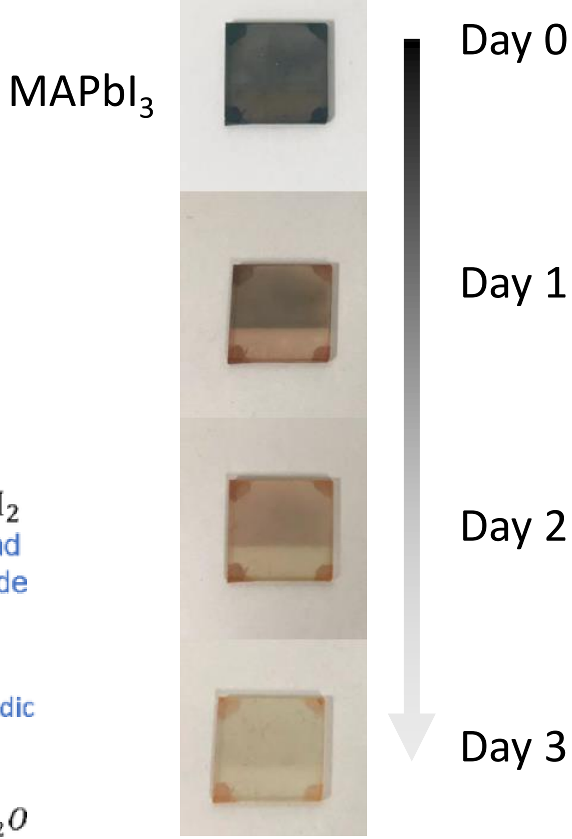
MAPbI$_3$ — Aqueous MAPbI — Lead Iodide

$CH_3NH_3PbI \leftrightarrow CH_3NH_2 + HI$

Aqueous MAPbI — Methylamine — Hydroiodic Acid

$O_2 + 4HI \leftrightarrow 2I_2 + 2H_2O$

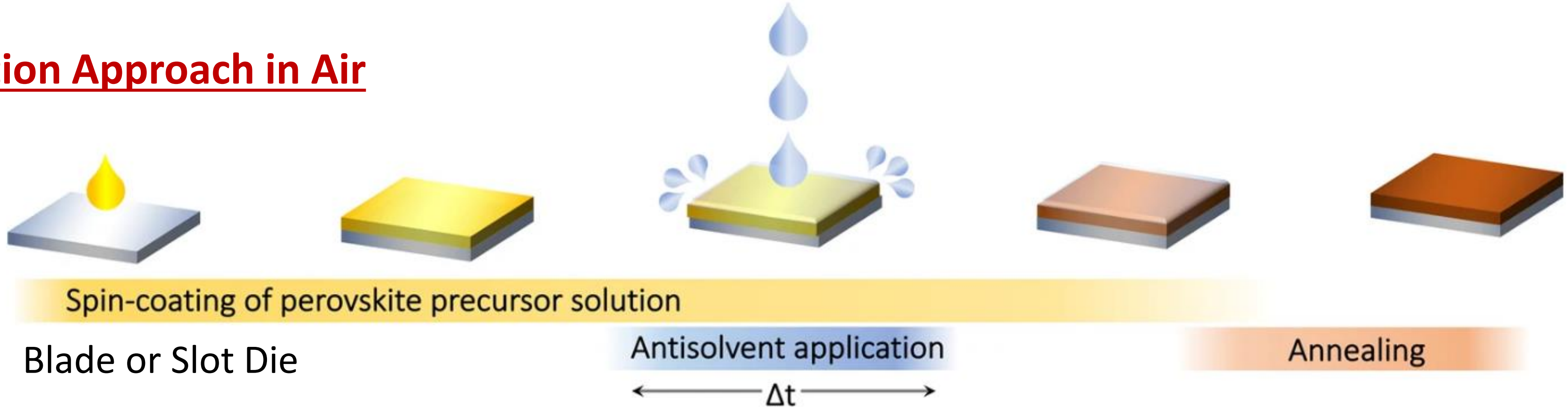
Hydroiodic Acid — Iodine



20 C, RH~50%

Synthesis of Perovskite Solar Cells

Solution Approach in Air

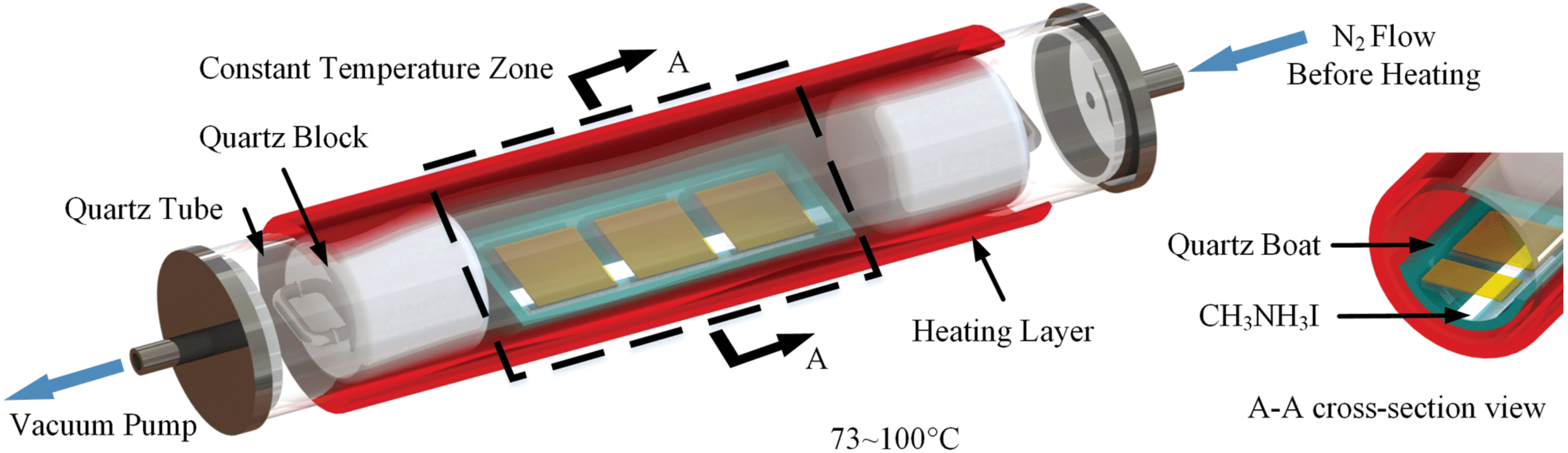


Blade or Slot Die

Gas quench or Vaccum

Nat Commun **12,** 1878 (2021)

Vapor Deposition Approach



$$PbI_2 + CH_3NH_3I \xrightarrow[15\sim30\text{mTorr}]{73\sim100°C} CH_3NH_3PbI_3$$

J. Mater. Chem. A, 2015, 3, 12436-12442

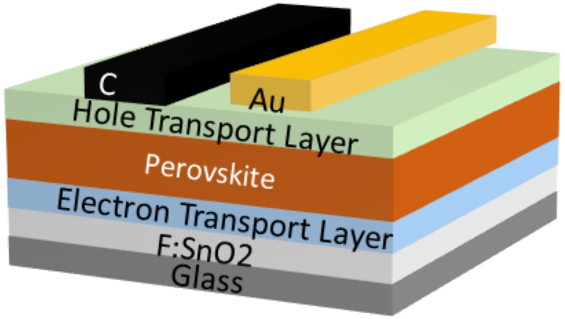
Carbon-electrode Based Perovskite Solar Cells

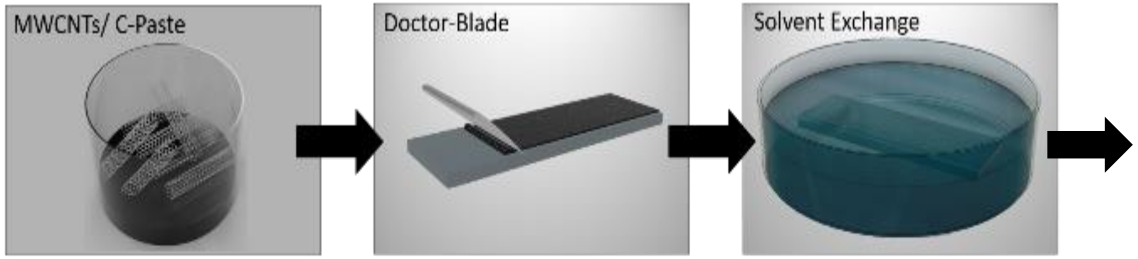
Our Perovskite thin film solar cells research focus

- ***Low-cost Carbon electrode*** *($0.006/g, 1/100000 cost of the Au) e.g.,* ***Carbon soot, coal***
- *Water hydrophobic*

Carbon issue

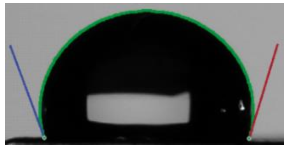
- *Traditional Carbon paste issue is that high resistive with polymer binder*

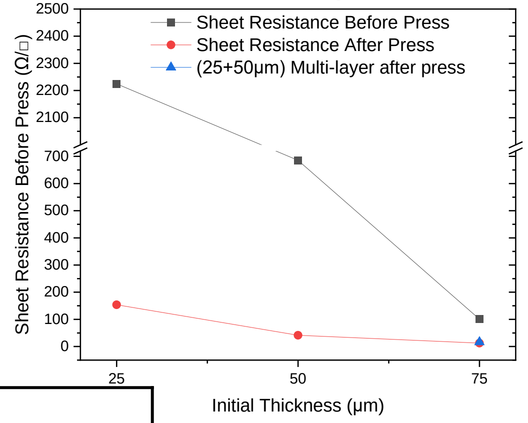


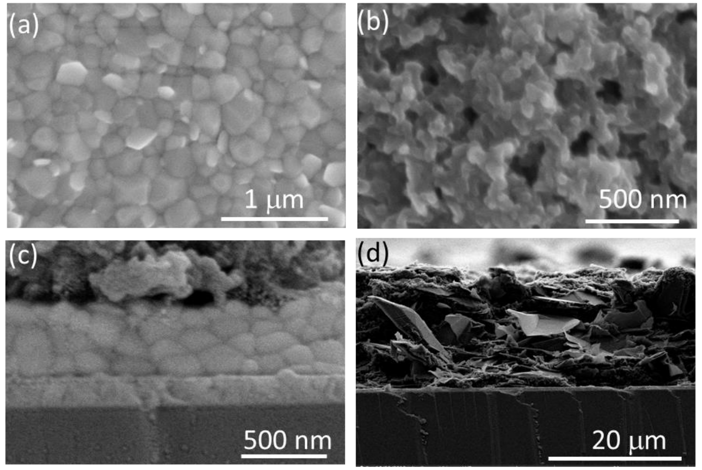


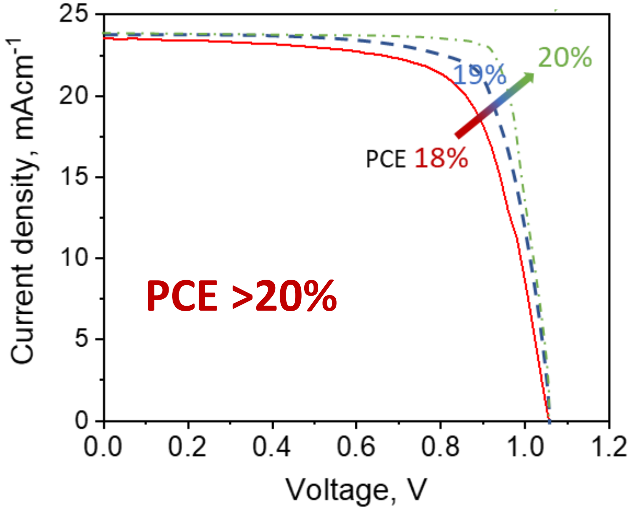
Carbon electrode

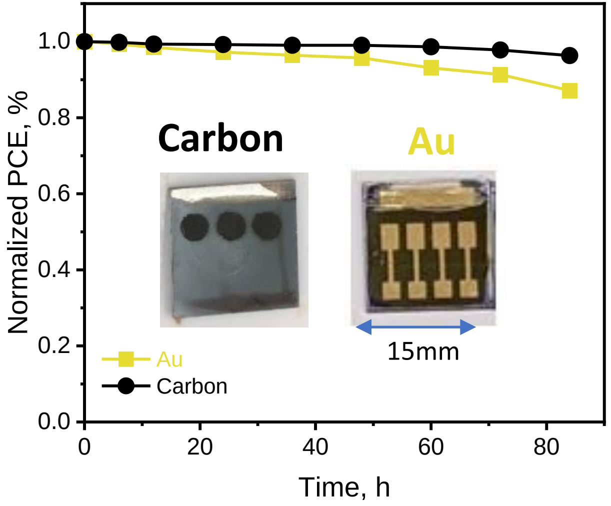
Hydrophobic





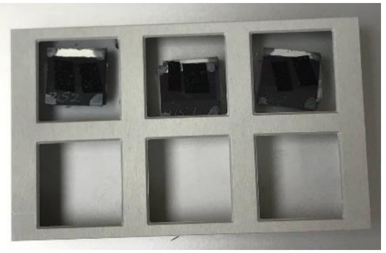






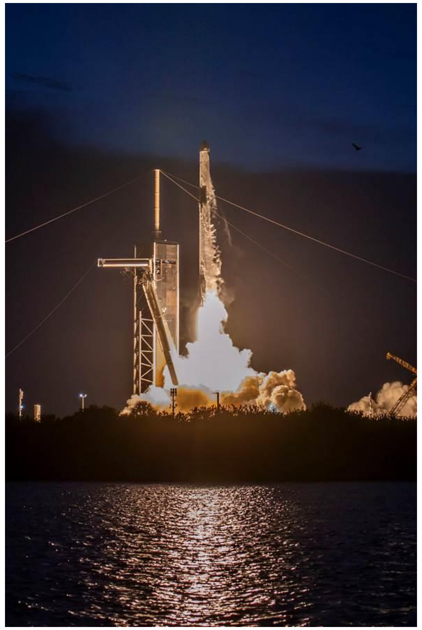
Yan, etc. Materials Today Physics, 2020, 13, 100204, 2020

Carbon-electrode Perovskite Solar Cells for Space Application

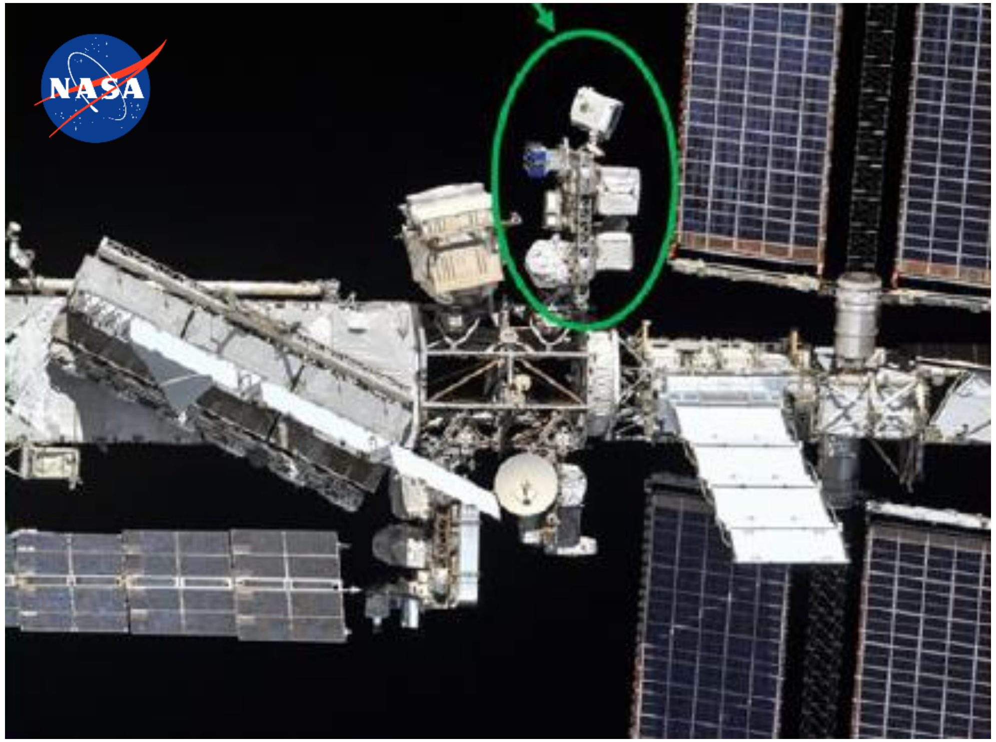


- **High efficiency**
- **Ultralight**
- **Stable in space**

MISS-16 Task

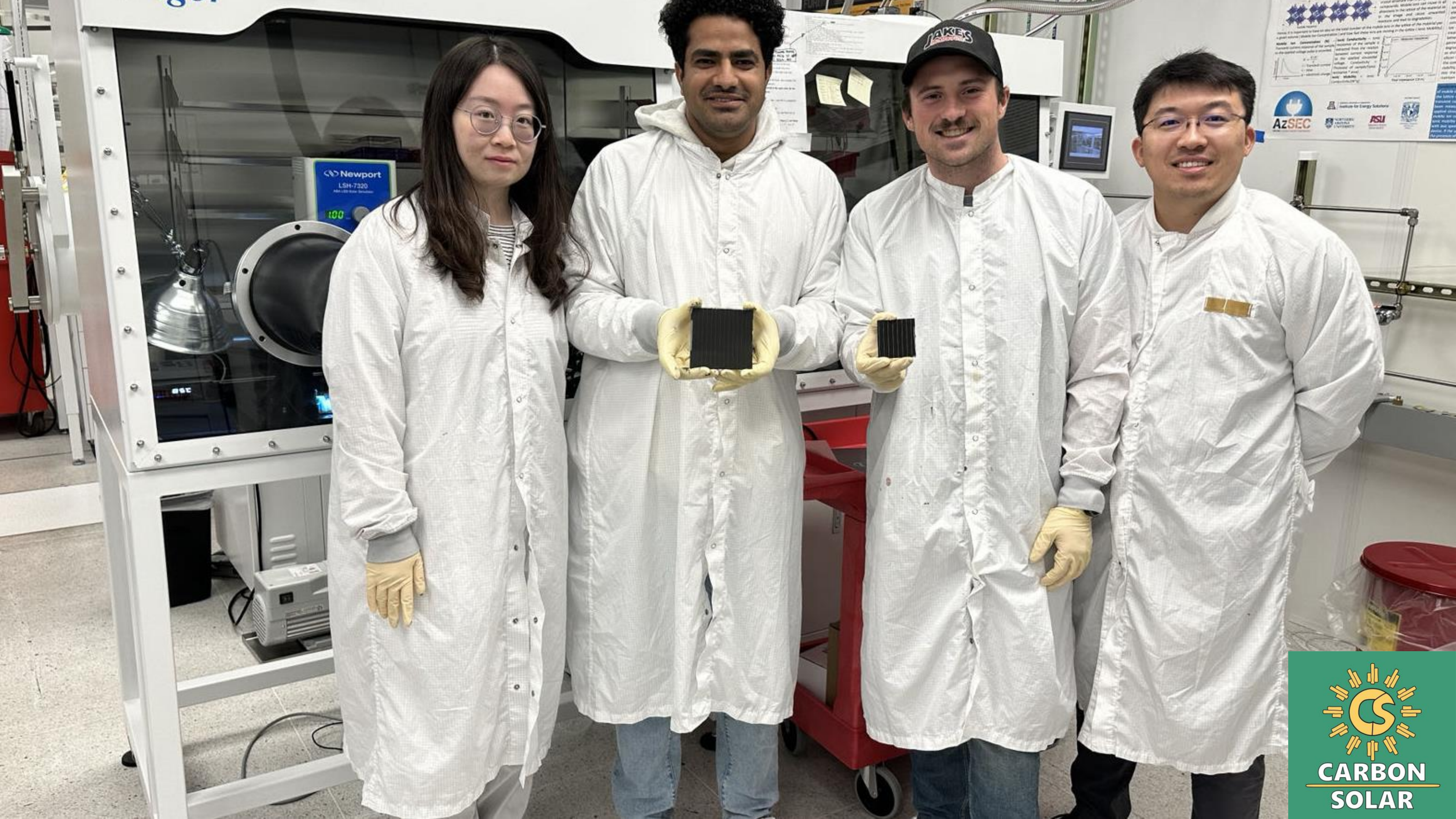


SpaceX CRS-25 Launch



- Launch from **Kennedy Space Center** on LC-39A
- Date/time: 15 Jul 22 at 00:44 UTC
- News Article: https://spacenews.com/spacex-launches-cargo-dragon-mission-to-iss/
- Photos: credit to NASA

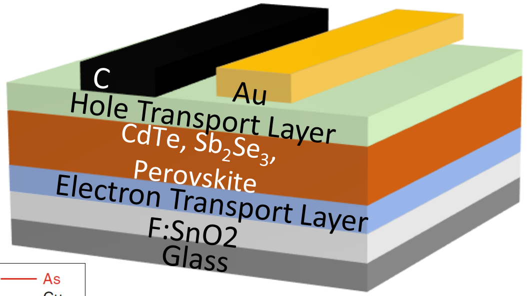
Yan, etc. Materials Today Physics, 2020, 13, 100204, 2020

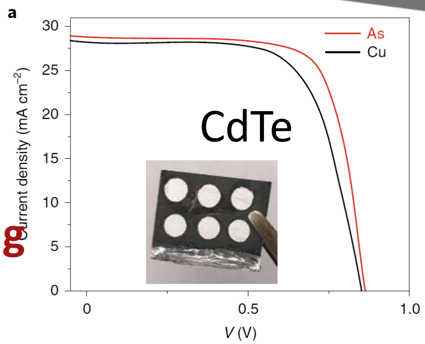


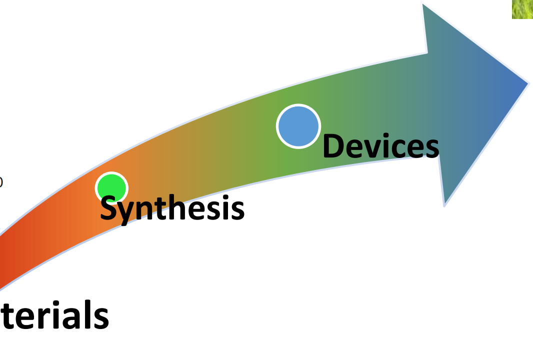
CARBON
SOLAR

Summary

- **Climate Change, EV, and Solar Energy**
  - **Climate Change & EV**
  - **Why solar?**
  - **Solar cells.**
- **Chalcogenides Thin Films Solar Cells**
  - **CdTe Thin Film Solar Cell**
    - **Doping Strategy: ex-situ Group V doping**
  - **Sb_2Se_3 thin film solar cells**
    - **Close space sublimated Sb_2Se_3 solar cells.**
- **Carbon-based Perovskite Solar Cell**
  - **Stability and High Efficiency**
  - **Low-cost Manufacturing Approach**

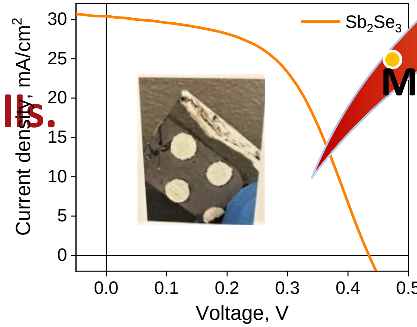


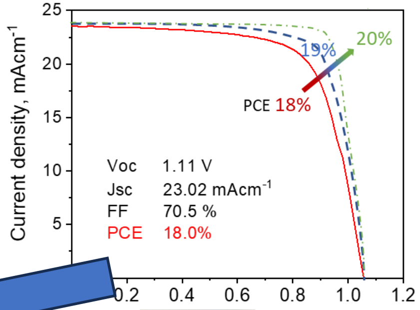


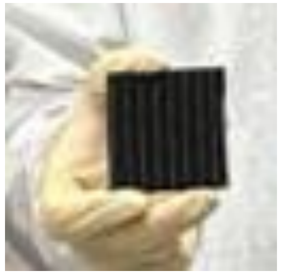


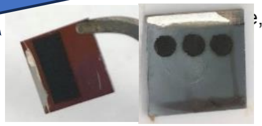
Key Research Foci:

- Higher **Efficiency**
- **Reliability**
- **Cost**-effectiveness
- **Scalability**









Perovskite

Thanks!

Q & A

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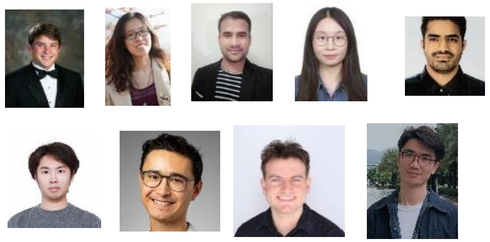
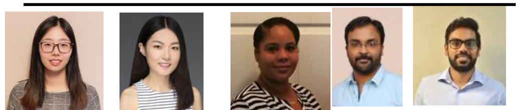
SYDNEY

Acknowledgement:

Current Graduate Students



Previous Graduate Students



Funding Agencies

Arizona State University
NSF
United States of America Department of Energy
SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy
NASA
USDA
NIFA
ORAU
NREL Transforming ENERGY
RAPID Transforming Process Industries
AEOP ARMY EDUCATIONAL OUTREACH PROGRAM
U.S. AIR FORCE
AFRL - SFFP SUMMER FACULTY FELLOWSHIP PROGRAM
US-MAC Manufacturing of Advanced Cadmium Telluride

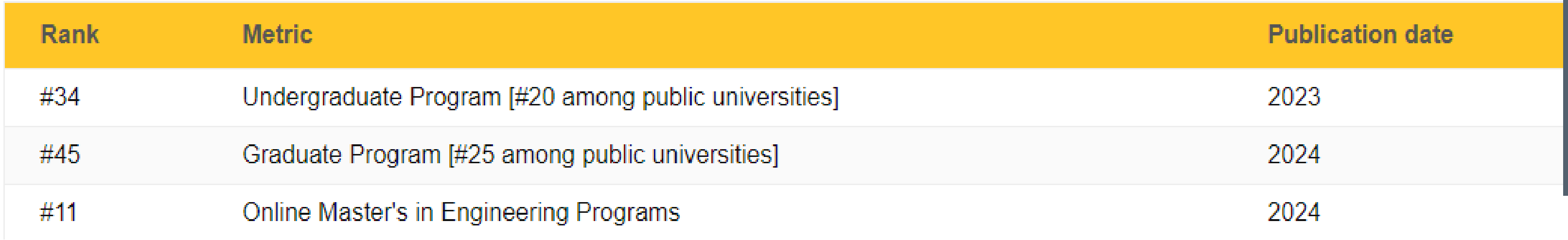
US Collaborations

First Solar
CORNING
Novelis
NREL Transforming ENERGY
OAK RIDGE National Laboratory
University of Central Florida
The University of Toledo 1872
Texas A&M University
1865 The University of Maine
University of Nevada, Reno
The University of Alabama
Colorado State University

Ira A. Fulton Schools of Engineering

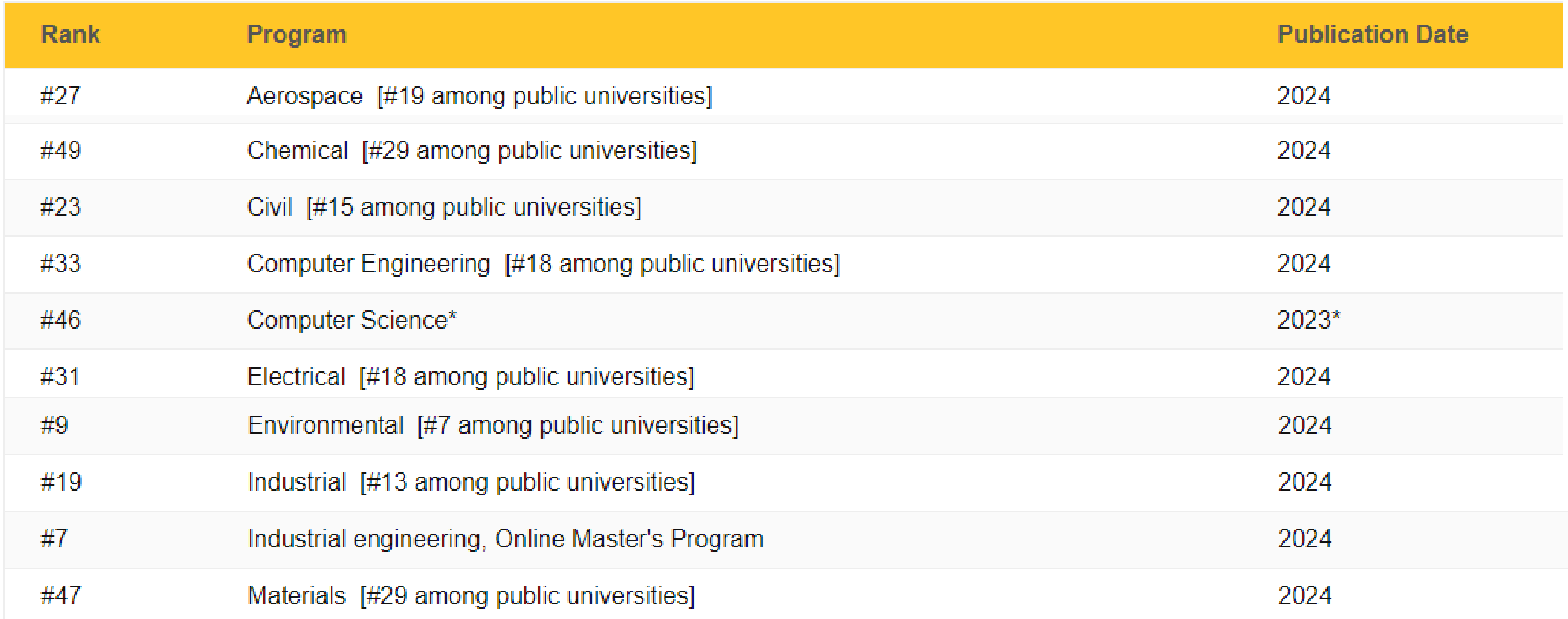
Arizona State University

U.S. News & World Report Rankings



Rank	Metric	Publication date
#34	Undergraduate Program [#20 among public universities]	2023
#45	Graduate Program [#25 among public universities]	2024
#11	Online Master's in Engineering Programs	2024

U.S. News & World Report Graduate School Specialty Rankings



Rank	Program	Publication Date
#27	Aerospace [#19 among public universities]	2024
#49	Chemical [#29 among public universities]	2024
#23	Civil [#15 among public universities]	2024
#33	Computer Engineering [#18 among public universities]	2024
#46	Computer Science*	2023*
#31	Electrical [#18 among public universities]	2024
#9	Environmental [#7 among public universities]	2024
#19	Industrial [#13 among public universities]	2024
#7	Industrial engineering, Online Master's Program	2024
#47	Materials [#29 among public universities]	2024

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Materials science and engineering (MS, Online MS, and PhD)

Materials research is a rapidly evolving arm of the engineering community. Using imagination, curiosity, testing and tools as fuel for discovery, materials science is helping us to understand the structure-property relationships of nanomaterials, and applications in energy, security and sustainability.

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