III-V solar cells
research and applications

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Content

- Wafer-based III-V cells, current status
- How to make better use of the solar spectrum
- Minimizing semiconductor material use
  while optimizing individual sub-cell performance
- Summary

Current applications

credits: ESA

Spacecraft

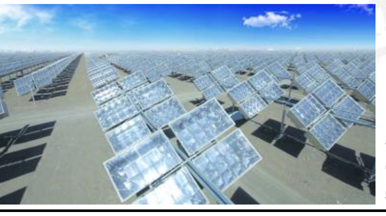
Mars Rover, credits: NASA

Current applications

Concentrated PV
DNI >2400 kWh/m²/yr

Arzon Solar (Amonix)
Alamosa Colorado, 35 MWp
504 Amonix 7700 systems

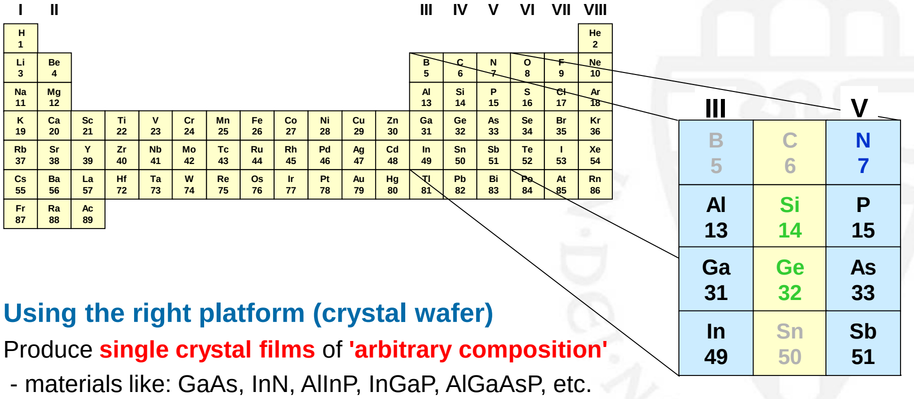
STACE (Concentrix/Soitec CPV)
Touwsriver, 44 MWp
1500 Soitec CX-S530 II systems



Suncore (Emcore)
Colmud 1&2: 138 MWp
5468 Suncore Gen3.5 systems

What are III-V semiconductors ?

Crystals formed by a 1 to 1 combination of elements from group III and V of the periodic table



Using the right platform (crystal wafer)

Produce **single crystal films** of **'arbitrary composition'**
- materials like: GaAs, InN, AlInP, InGaP, AlGaAsP, etc.
- **tune material properties** by choosing right composition

From single-junction to multi-junction cells

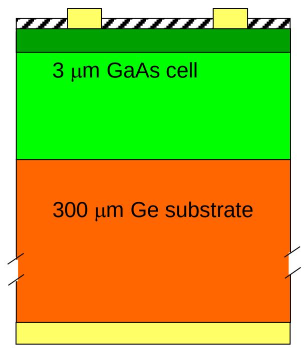
Single junction III-V cell

GaAs (theory: >30%)

WR: ~~25.1% (Kopin,VS, 1990)~~

~~26.1% (Radboud 2008)*~~

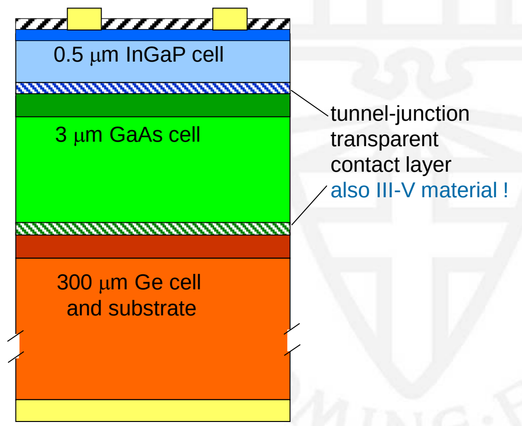
27.5% (LG 2015)



Triple-junction III-V cell

InGaP/GaAs/Ge (theory: >40%)

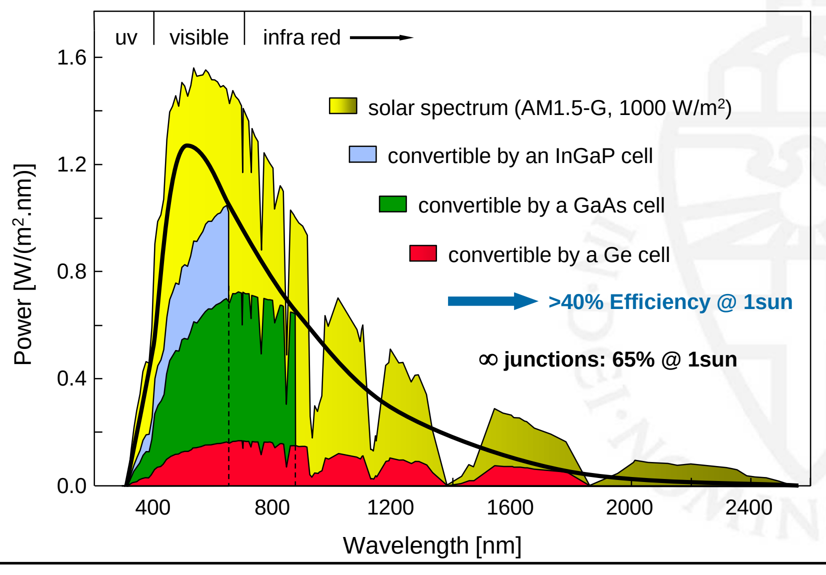
WR: 33.2% (ISE-Fraunhofer, 2011)



* Bauhuis et al. Sol. Ener. Mat.&Sol. Cells 93 (2009) 1488

Irradiated and convertible power

Theory: including V_{oc} and FF diode losses & current matching

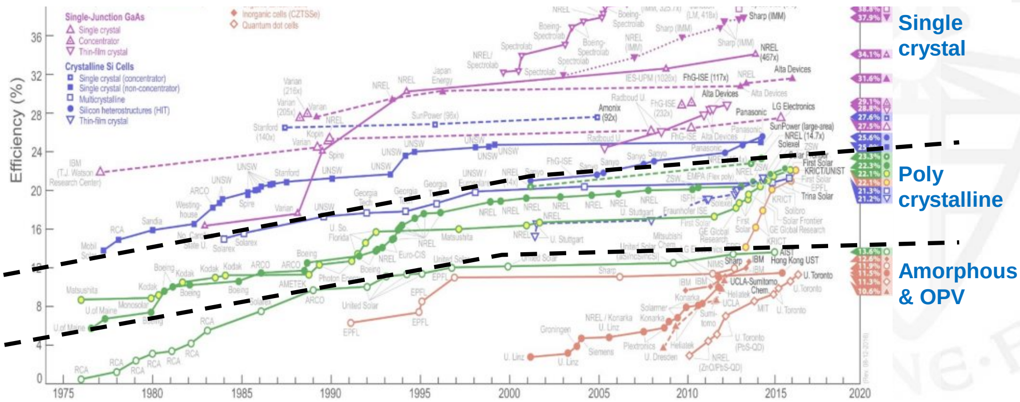


In practice: best research cell efficiencies

Perfect single crystals (low defect density) for high efficiency cells

➔ **Epitaxial growth** on substrate with **matching lattice**

Which semi-conductors to combine to utilise the entire solar spectrum?

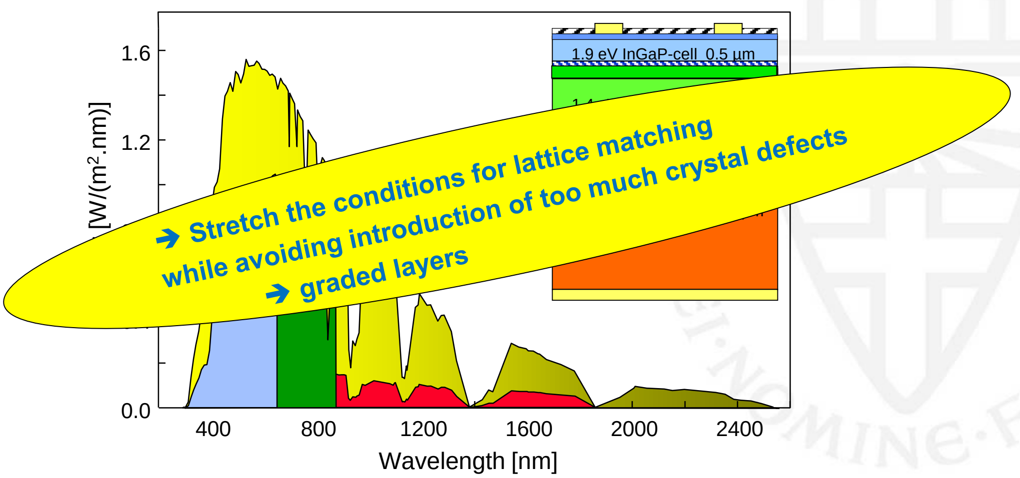


Optimal PV solar energy harvesting

Compared to lattice matched InGaP/GaAs/Ge 3J benchmark

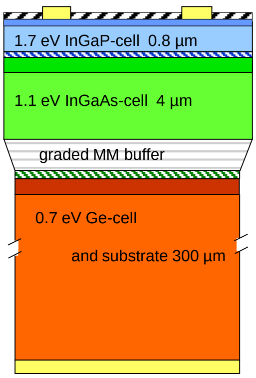
InGaP & GaAs current matched, Ge twice the current

Efficiency ~ 32% @ 1 sun



Position the top cells better

Upright MetaMorphic (UMM) cell



Compared to InGaP/GaAs/Ge benchmark

In↑ ➔ V_{OC}↓ but J_{SC}↑↑

- 33.2% @ 1 sun (Fhg-ISE)
- 41.6% @ 364 suns (Boeing Spectrolab)

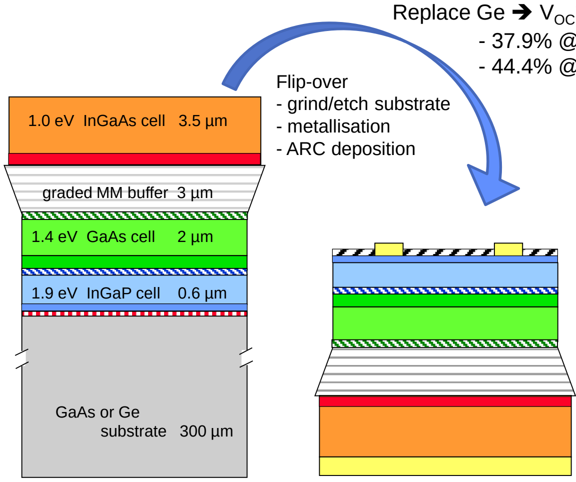
Position the bottom cell better

Inverted MetaMorphic (IMM) cell

Compared to InGaP/GaAs/Ge benchmark

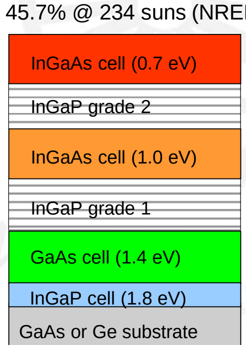
Replace Ge ➔ V_{OC}↑↑ while J_{SC} remains constant

- 37.9% @ 1 sun (Sharp)
- 44.4% @ 302 suns (Sharp)



Do the trick twice ➔ 4j cell

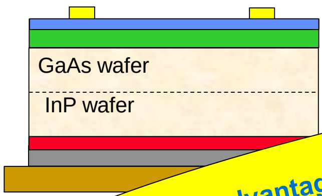
- 45.7% @ 234 suns (NREL)



Mechanically stacked double tandem

Wafer bonding type 4J/2 terminal

InGaP/GaAs - InGaAsP/InGaAs

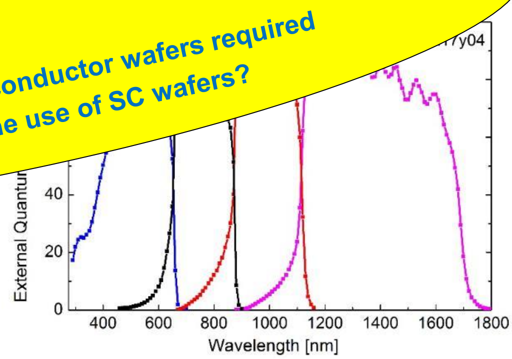


Compared to InGaP/GaAs/Ge benchmark

V_{OC}↑↑↑ while J_{SC} remains the same

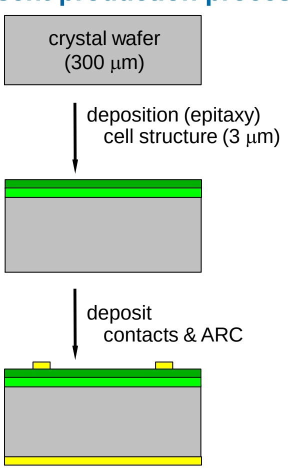
- 46% @ 508 suns

Major disadvantage
not 1 but 2 precious semiconductor wafers required
➔ can we avoid the use of SC wafers?



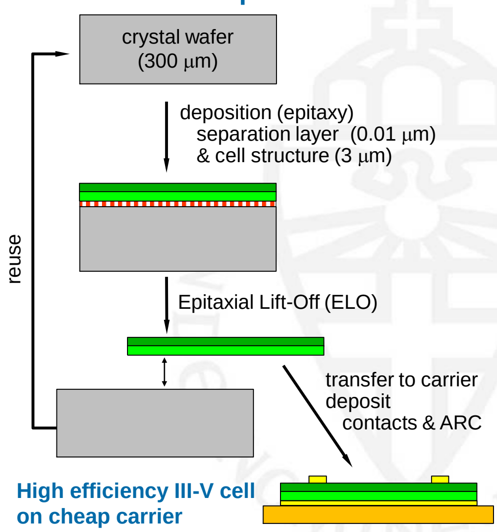
Epitaxial Lift-Off for substrate reuse

Present production process



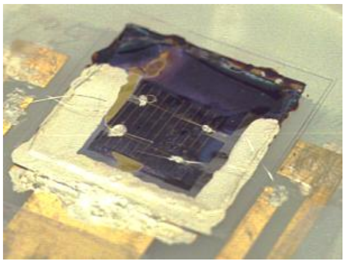
High efficiency III-V cell on expensive wafer

ELO thin-film cell process



High efficiency III-V cell on cheap carrier

Processing thin-film GaAs cells



1996: first thin-film GaAs cell (η =10%)

Challenge

no "standard" processing technology

thin III-V film and foreign carrier have different properties

process development & perseverance

World record cell efficiencies

2005: 24.5% thin-film cell (2 µm) [1)]

2008: 26.1% substrate cell (3.5 µm) [2)]

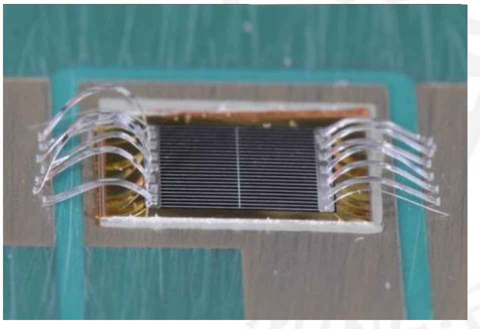
2009: 26.1% thin-film cell (2 µm) [2)]

2011: 28.8% thin-film cell (AltaDevices)

2016: 29.3% thin-film cell @ 50 suns (LG)

2016: 31.6% thin-film tandem (AltaDevices)

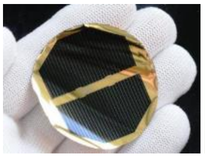
31.7% thin-film tandem @ 300 suns

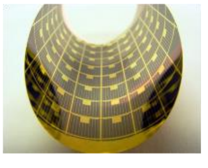


[1)] Schermer et al. Thin Sol. Films 511 (2006) 645

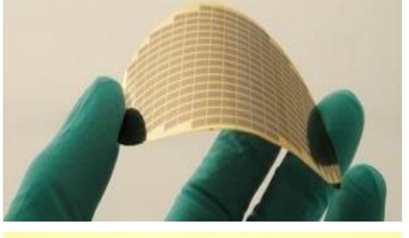
[2)] Bauhuis et al. Sol. Ener. Mat.&Sol. Cells 93 (2009) 1488

Wafer-size thin-film cell processing

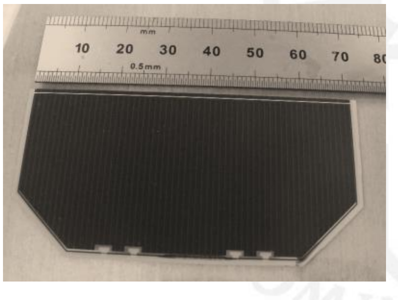


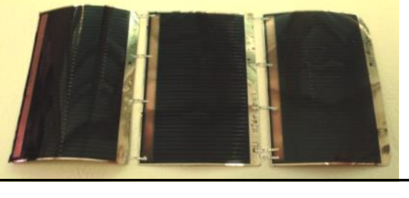


2” epi-film processed
at Radboud University



4” epi-film processed
at spin-out tf2-devices





String of cells
processed from 4" epi-film

Potential other ELO cell applications

Unmanned Aerial Vehicles (UAV)

High-altitude pseudo satellites (HAPS)

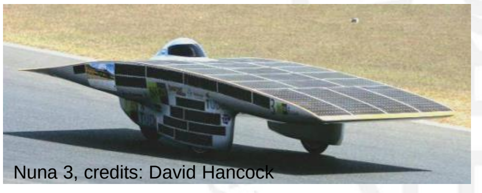
Zephyr T, credits: Airbus

Transport (PV powered cars)

Solar Challenge Australia
- University of Delft/Twente
- University of Eindhoven / Lightyear

Producers aiming for III-V

Hanergy & Audi / Toyota



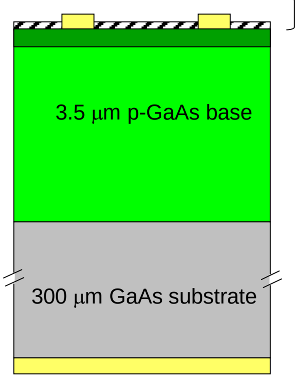
Nuna 3, credits: David Hancock

High-end consumer products

- Laptops
- Smart phones

Make the most of each sub-cell

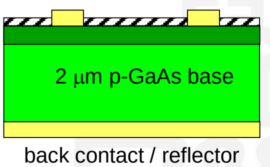
26.1% wafer based cell



back contact

grid contact / ARC

26.1% thin-film cell



back contact / reflector

Thin-film vs. substrate-based III-V cells

- less mature thin-film cell processing

+ less SC material required (substrate and epi-layer!)

+ no escape of photons to substrate

➔ increased photon recycling

+ low weight, flexible, less heat resistance

Thin-film geometry in principle superior

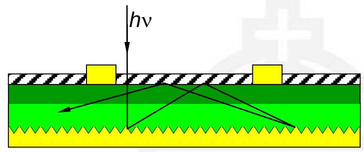
➔ optimisation of the individual junctions

Thin-film cell theoretically superior

How to maximize this advantage

1) Further minimize epilayer thickness

- increase light-path by surface structuring



2) Optimize photon recycling

➔ effective increase in light concentration V_{oc} ↑

- maximize mirror reflectivity > 90% ➔ more than linear increase in V_{oc} [1)]

Thin Film cells	V_{oc} [V]	J_{sc} [mA/cm²]	FF [%]	Efficiency [%]
Radboud University	**1.045**	29.5	84.6	26.1
Alta Devices WR	**1.122**	29.68	86.5	28.8

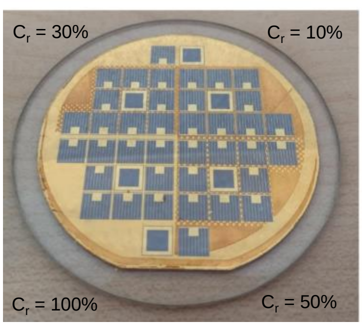
[1)] Miller et al., J. Photovolt. 2 (2012) 303

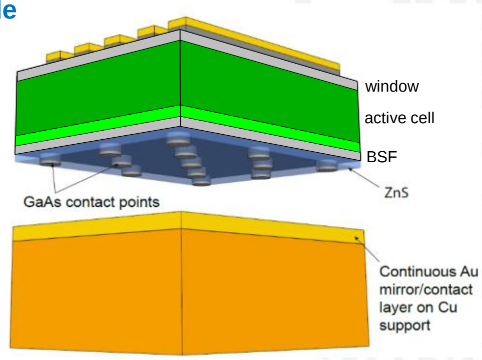
Maximize rear-mirror reflectivity

Avoid absorption in highly doped GaAs contact layer [1)]

- partly remove back-contact layer → contact points
- fill the gaps with transparent dielectric (ZnS)
  - ➔ theoretically >30% gain in reflection of reemitted photons

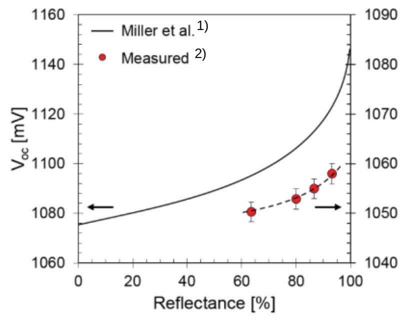
Experimental proof of principle





[1)] Gruginskie et al., Thin Solid Films 660 (2018) 10

V_{oc} upon increased reflectance



Onset of theoretically predicted super linear increase of V_{oc} with reflectance

Important note

Gain in V_{oc} only obtained for deep-junction[3] thin-film cell

➔ cell operates mainly in the radiative recombination regime

1) Miller, Yablonovitch and Kurtz, J. Photovolt. 2 (2012) 303
2) Gruginskie et al.,Thin Solid Films 660 (2018) 10
3) Bauhuis et al., Phys. Stat. Sol. A 231 (2016) 2216

Summary / context

Present III-V cell production (InGaP/GaAs/Ge 3J benchmark)

wafer-based + batch production → high costs

Spacecraft

Concentrator systems in regions with high DNI

- 500-1000x less semi-conductor area & up to 40% cell efficiency
- slow revival, technology from 3 largest producers has passed on

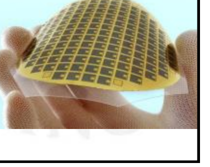
Research

Brute force: apply better fitting or more sub-cells

- step by step extension of CPV to regions with lower DNI
- multifunctional BICPV concepts (start-up companies)

Make the most of each junction

- minimize film cell thickness by maximizing photon confinement photo recycling



Options for cost reduction and additional applications

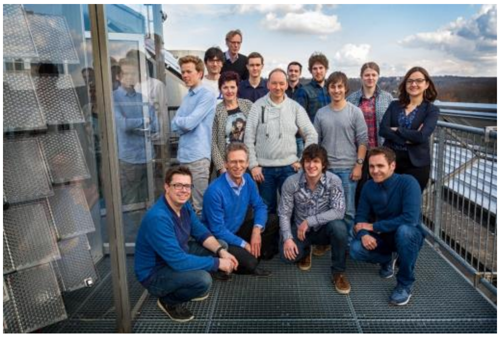
Wafer reuse (ELO, 100x less semi-conductor thickness)

- flexible, light-weight modules for UAVs & transport (MicroLink, tf2-devices)

High throughput epi-deposition technology

- >30% flat-plate modules (AltaDevices/Hanergy, LG-electronics)

Acknowledgements



Staff and students Applied Materials Science group

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- tf2 devices
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CNPq Science without borders

eit RawMaterials Connecting matters

LG Life's Good

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