Photovoltaics with Highest Efficiencies

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www.ise.fraunhofer.de

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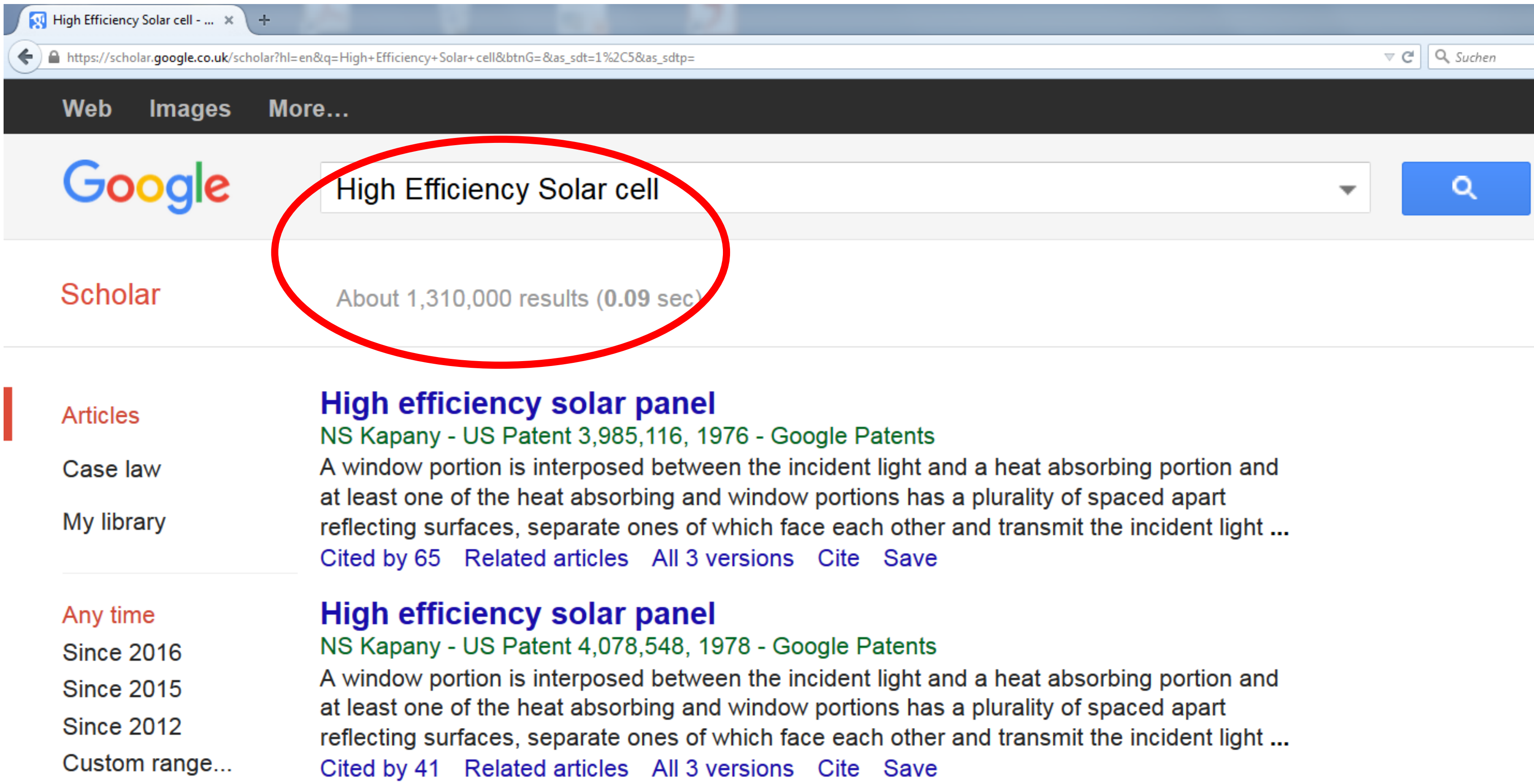
High Efficiency Solar Cell is a Hot Topic
Over 1.3 Million Search Results in Google Scholar!



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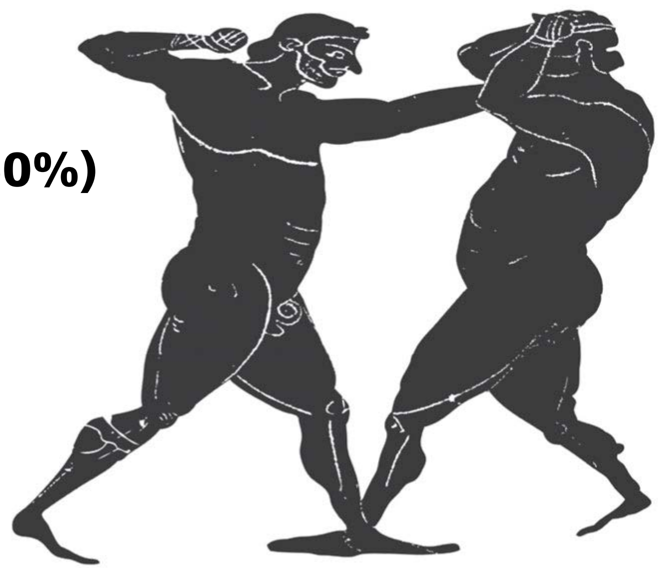
The “High Efficiency” PV-Championship

A Fight in Different Classes



Featherweight (5-10%)
Novel concepts,..

Heavyweight (45-50%)
III-V multi-junctions

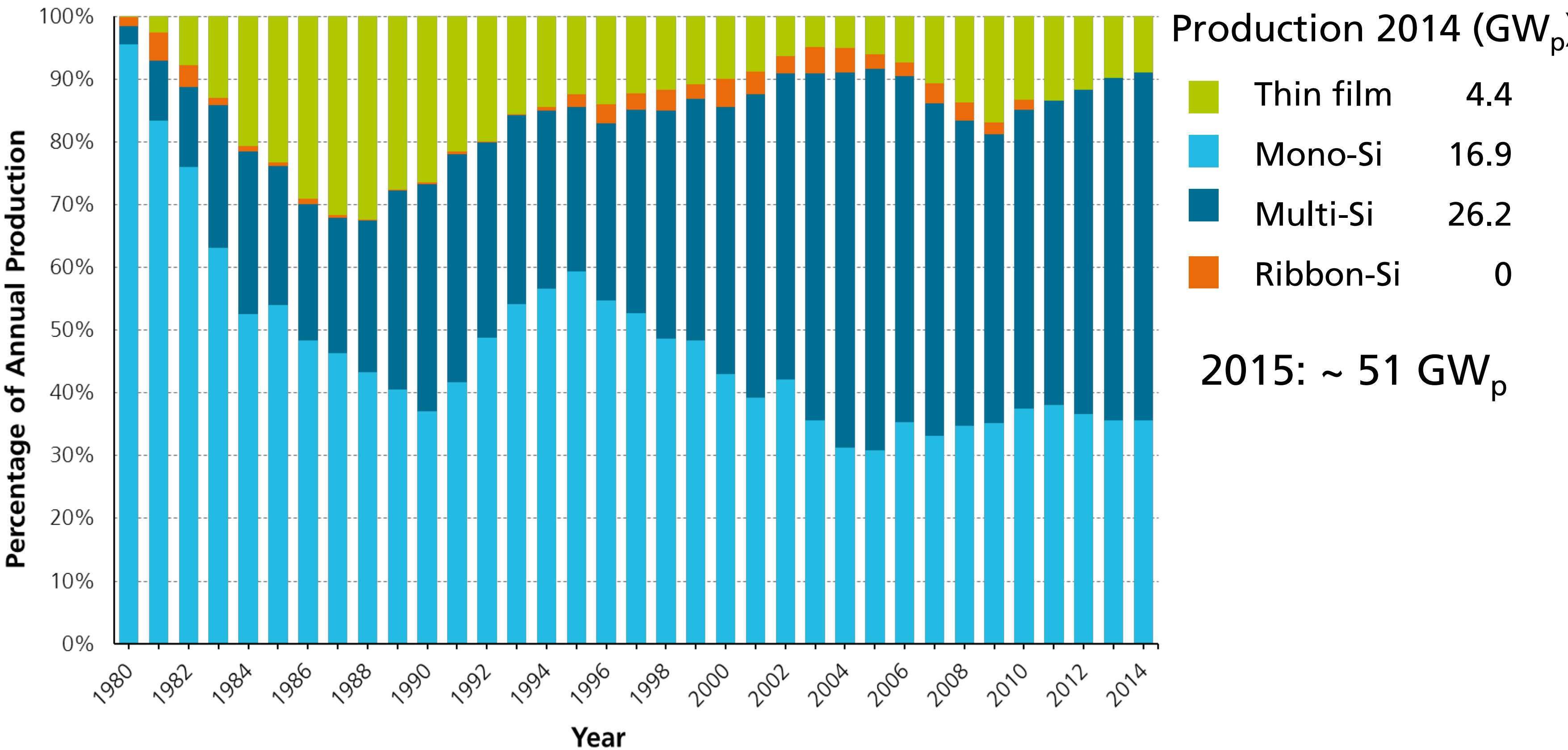
Lightweight (10-15%)
a-Si, dye-sensitized, organic, Pervoskite…

Cruiserweight (25-30%)
c-Si, Si concentrator, III-V single-junction

Middleweight (19-25%)
mc-Si, CIGS, CdTe , Pervoskite

Picture: N. Faulkner, A Visitor’s Guide to the Ancient Olympics, 2011

PV Production by Technology
Percentage of Global Annual Production



2015: ~ 51 GW_p

Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion by Paula Mints). Graph: PSE AG 2015

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Efficiency and Costs

Levelized Costs of Electricity LCOE

$$\text{LCOE}^{1} = \frac{\text{Total Cost}}{\text{Lifetime Energy Production}}$$

[1]LCOE = Levelized cost of energy

Efficiency and Costs

Levelized Costs of Electricity LCOE

$$\text{LCOE}^1 = \frac{\text{Total Cost}}{\text{Lifetime Energy Production}}$$

$$\approx \frac{\text{Total Cost}}{\textbf{Efficiency} \cdot \text{Irradiance}_{\textit{during Lifetime}}}$$

[1]LCOE = Levelized cost of energy

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Efficiency and Costs
Levelized Costs of Electricity LCOE

$$\text{LCOE}^{1} = \frac{\text{Total Cost}}{\text{Lifetime Energy Production}}$$

$$\approx \frac{\text{Total Cost}}{\textbf{Efficiency} \cdot \text{Irradiance}\ \textit{during Lifetime}}$$

Depends on technology

Depends on site

[1]LCOE = Levelized cost of energy

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Efficiency and Costs
Levelized Costs of Electricity LCOE

Increase the efficiencies to reduce costs!

- on cell level
- on module level
- on system level

$$LCOE^{1} = \frac{\text{Total Cost}}{\text{Lifetime Energy Production}}$$

$$\approx \frac{\text{Total Cost}}{\textbf{Efficiency} \cdot \text{Irradiance}_{\,during\ Lifetime}}$$

Depends on technology

Depends on site

[1]LCOE = Levelized cost of energy

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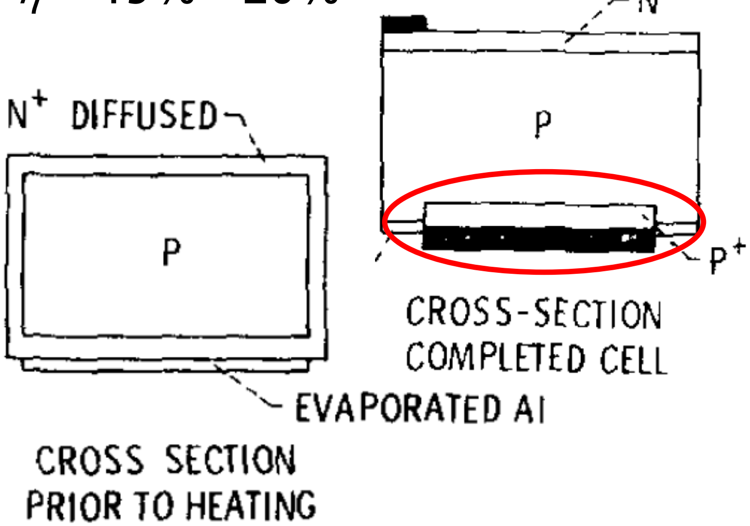
State-of-the-art 2016 for Silicon Solar Cells
Industry: Switching from Al-BSF to PRC

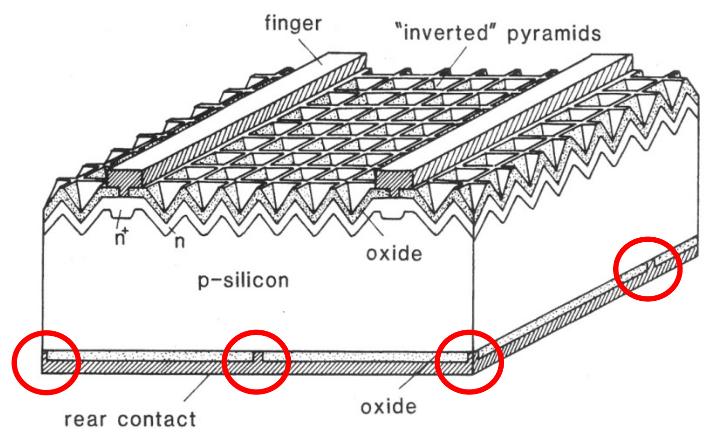
- Al-alloyed back surface field (Al-BSF) solar cells have dominated the industry for decades
- Partial rear contact cells (PRC) like PERC/PERL are introduced in production

η = 19% - 20%



Mandelkorn and Lamneck,
J. Appl. Phys. 44, 4785 (1973)

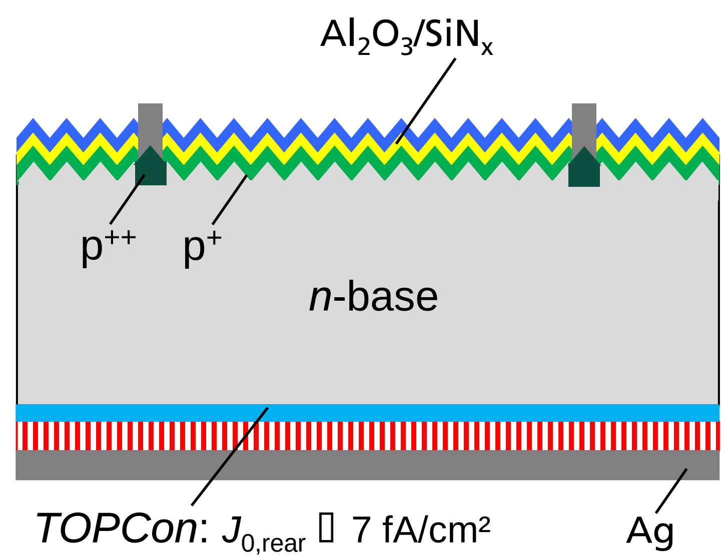
η = 20% - 21.5%



Blakers *et al.*,
Appl. Phys. Lett. 55, 1363 (1989)

High-Efficiency Si Solar Cells from Fraunhofer ISE
Diffused Front and TOPCon Rear

- Diffused boron emitter (150 Ω/sq)
  - Al_2O_3 passivation + ARC
  - Selective emitter structure
- n-type base
- **Full-area TOPCon rear side**
  → selective contacts
- Ag rear contact
- 1D cell architecture



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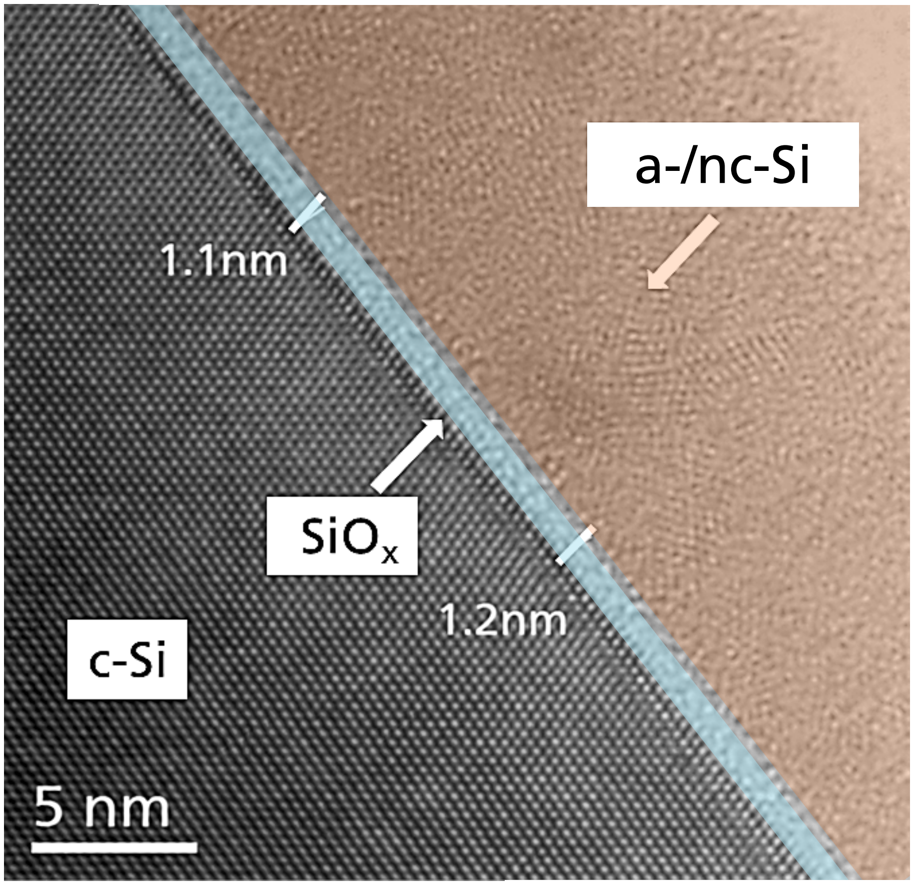
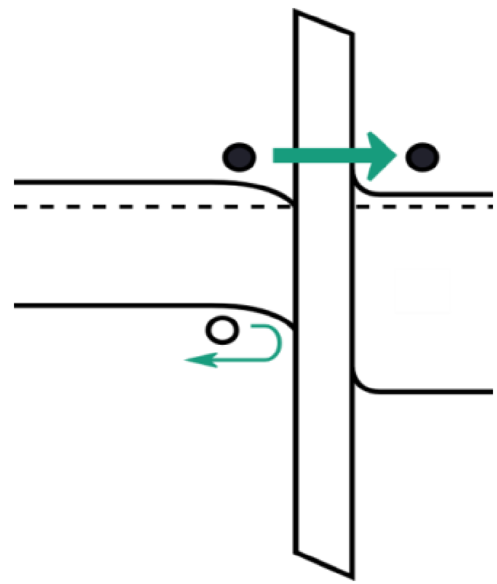
TOPCon (Tunnel Oxide Passivated Contact)

Combining a-Si Hetero and poly-Si/Tunnel Oxide Approach





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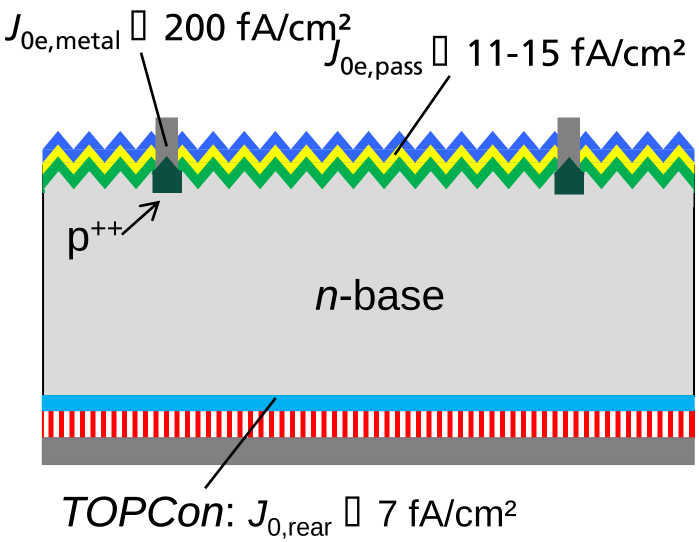
High-Efficiency Solar Cells from Fraunhofer ISE

Lab Cells with Top/Rear Contacts

	Material	V_{oc} [mV]	J_{sc} [mA/cm²]	*FF* [%]	η [%]
UNSW/PERL	*p*-type 400 µm	706	42.7	82.8	25.0
TOPCon	*n*-type 200 µm	718	42.1	83.2	**25.13***



* 4 cm² (da), confirmed by Fraunhofer ISE Callab

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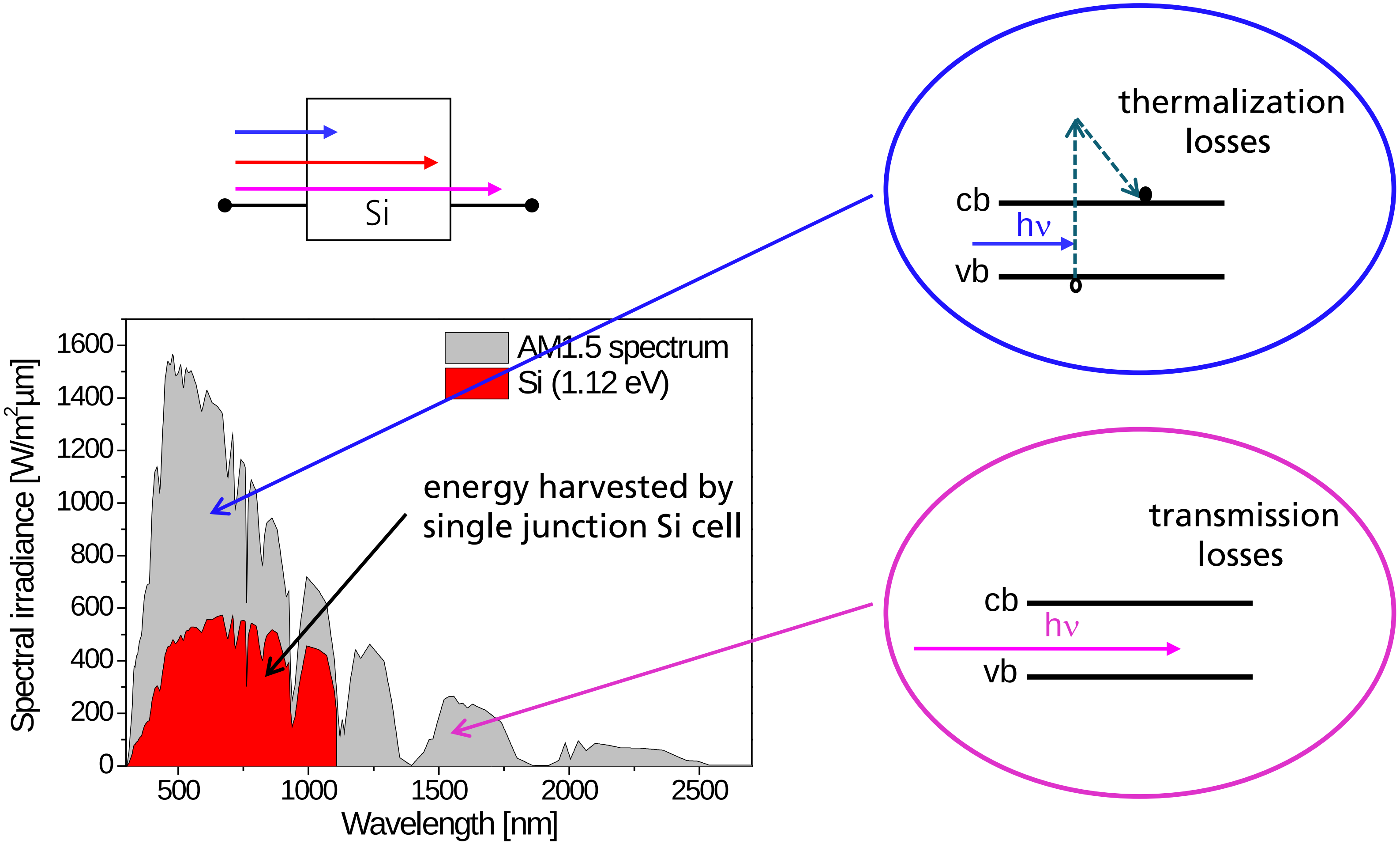
The Limits of Single-Junction Solar Cells
Thermalisation and Transmission Losses!



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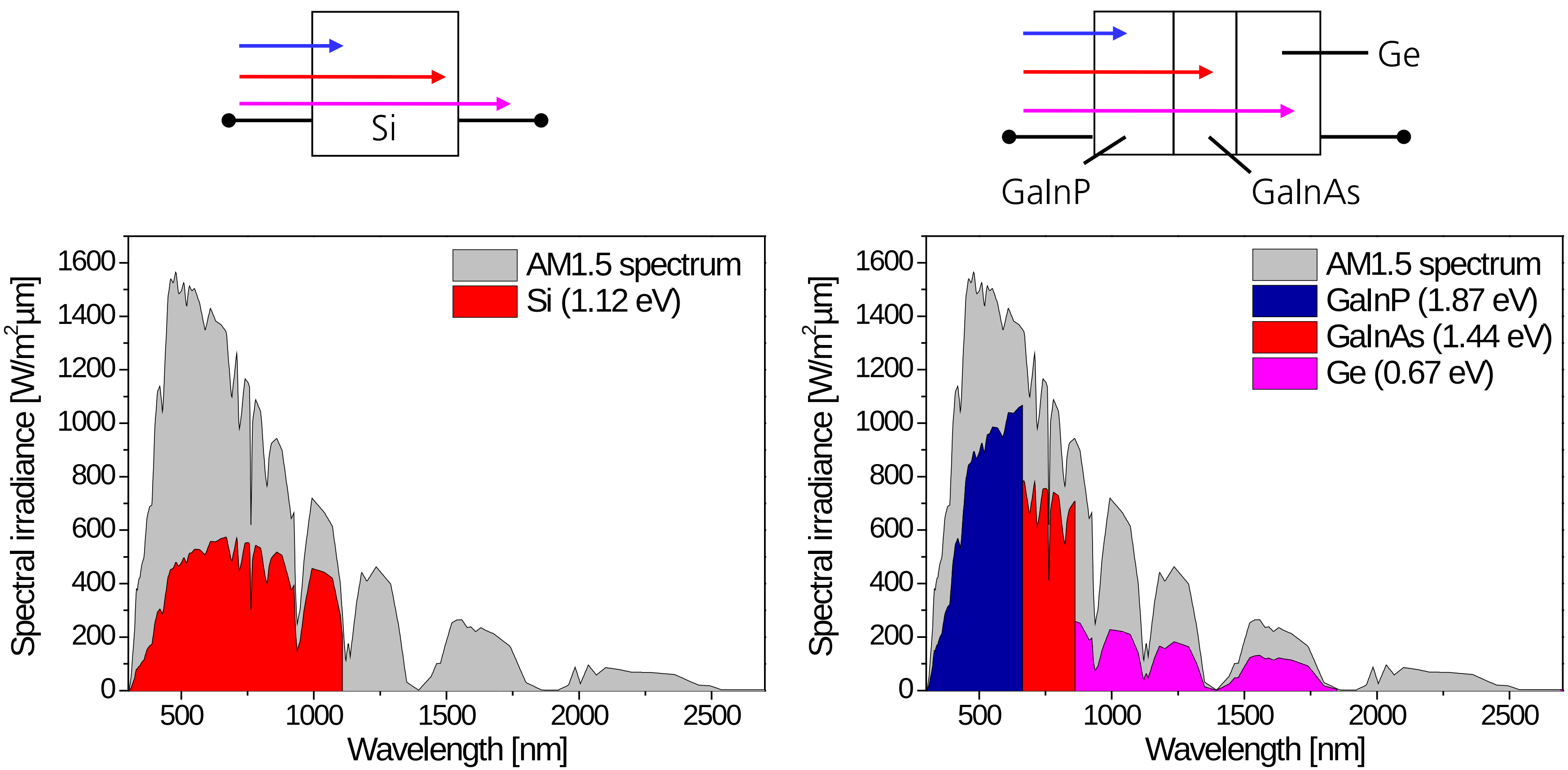
The Benefit of Multi-Junction Solar Cells

Reduction of Thermalisation and Transmission Losses!



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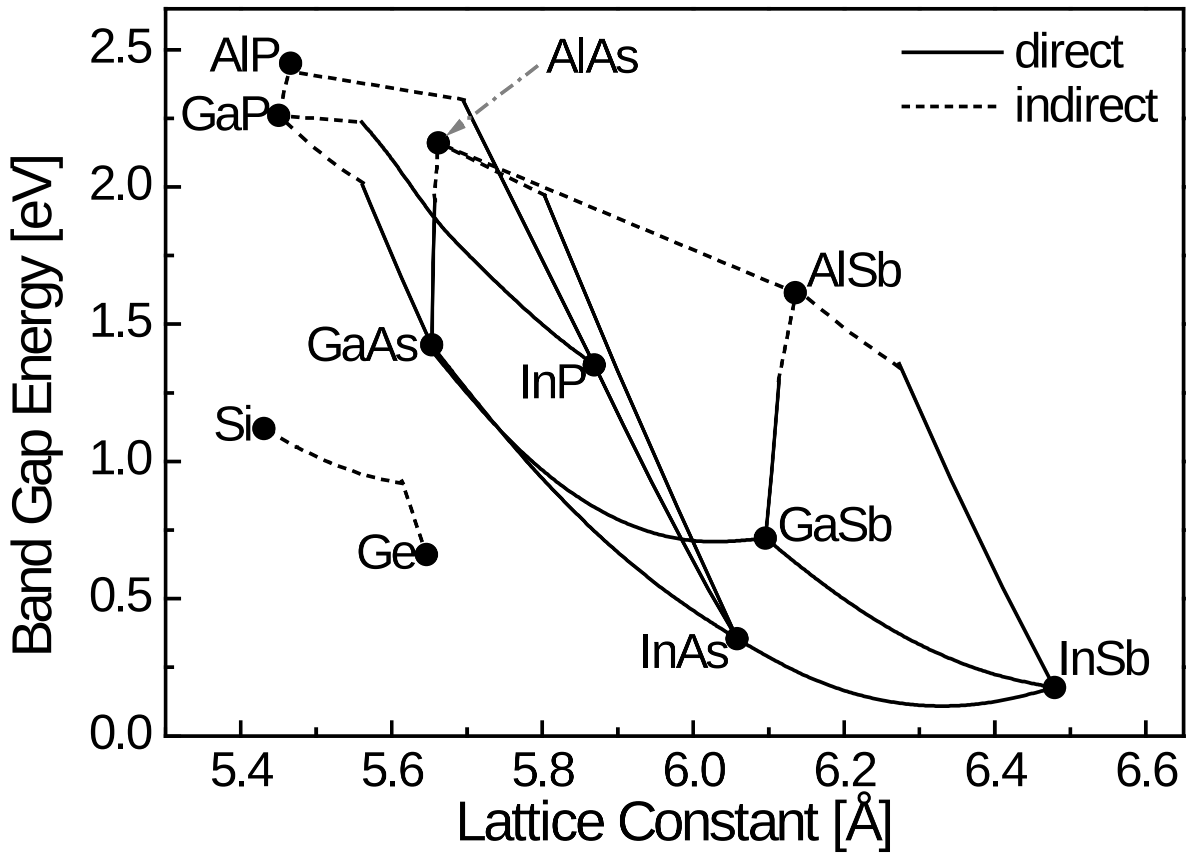
III-V Materials for Multi-junction Solar Cells

The Possibility to Design Bandgaps!

Highest material quality for lattice-matched epitaxy!



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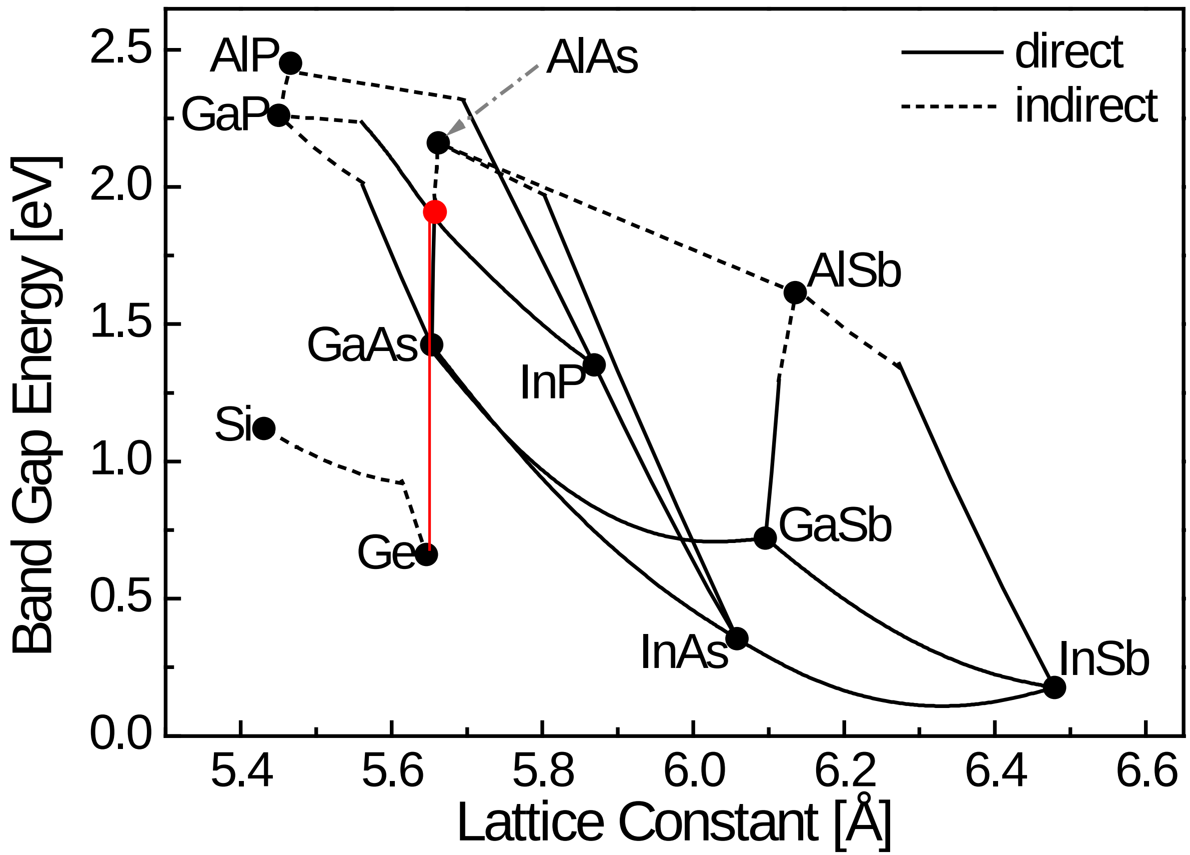
III-V Materials for Multi-junction Solar Cells
The Possibility to Design Bandgaps

Highest material quality for lattice-matched epitaxy!

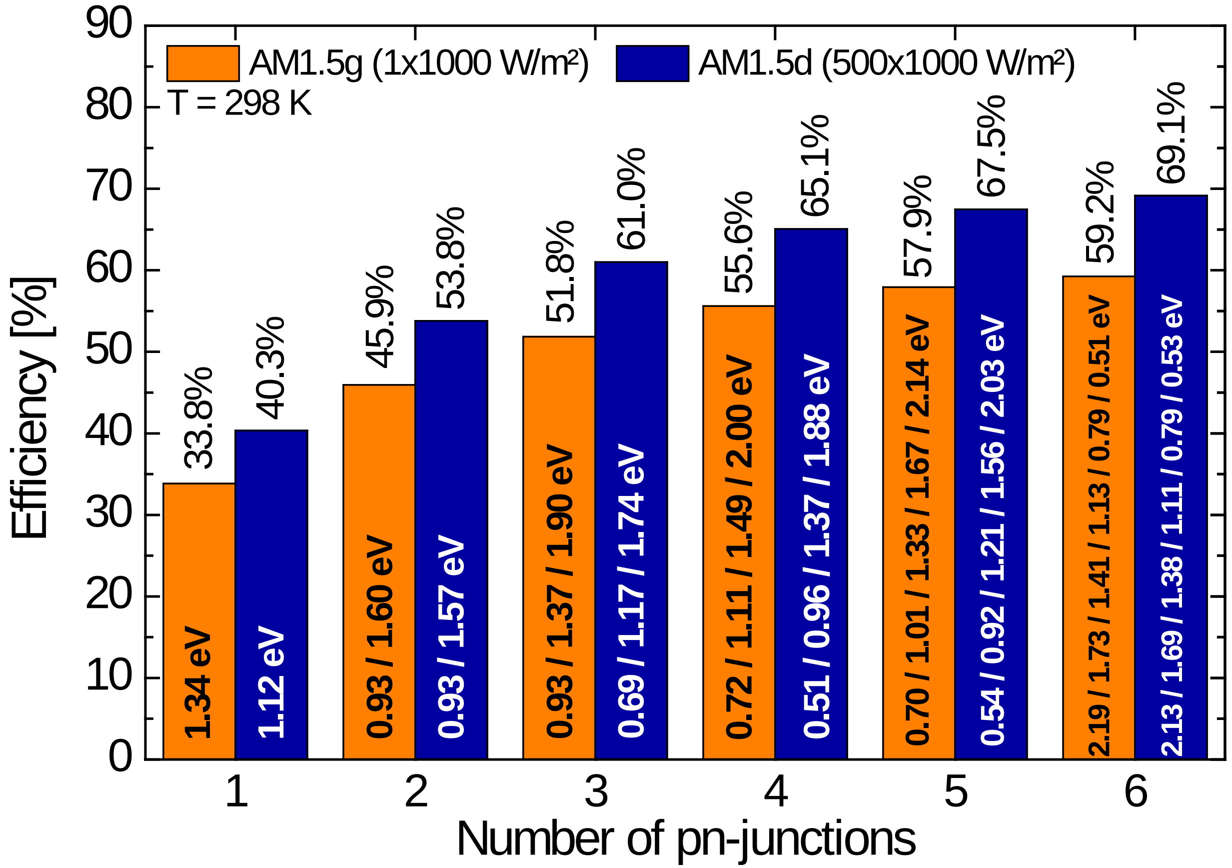
For example:

GaInP/GaAs/Ge
→ industry standard



What can be Expected from Multi-Junction Solar Cell?

50% Solar Cells are Realistically Achievable!



75 % - 80 % of limit efficiency is achievable in practical devices

→ 4j cell and concentrated light needed for 50 % cell

Calculation based on Shockley-Queisser approach

S.P. Philipps and A.W. Bett, in: Advanced Concepts in Photovoltaics, A, J. Nozik et al (eds.), Cambridge: Royal Society of Chemistry (2014).

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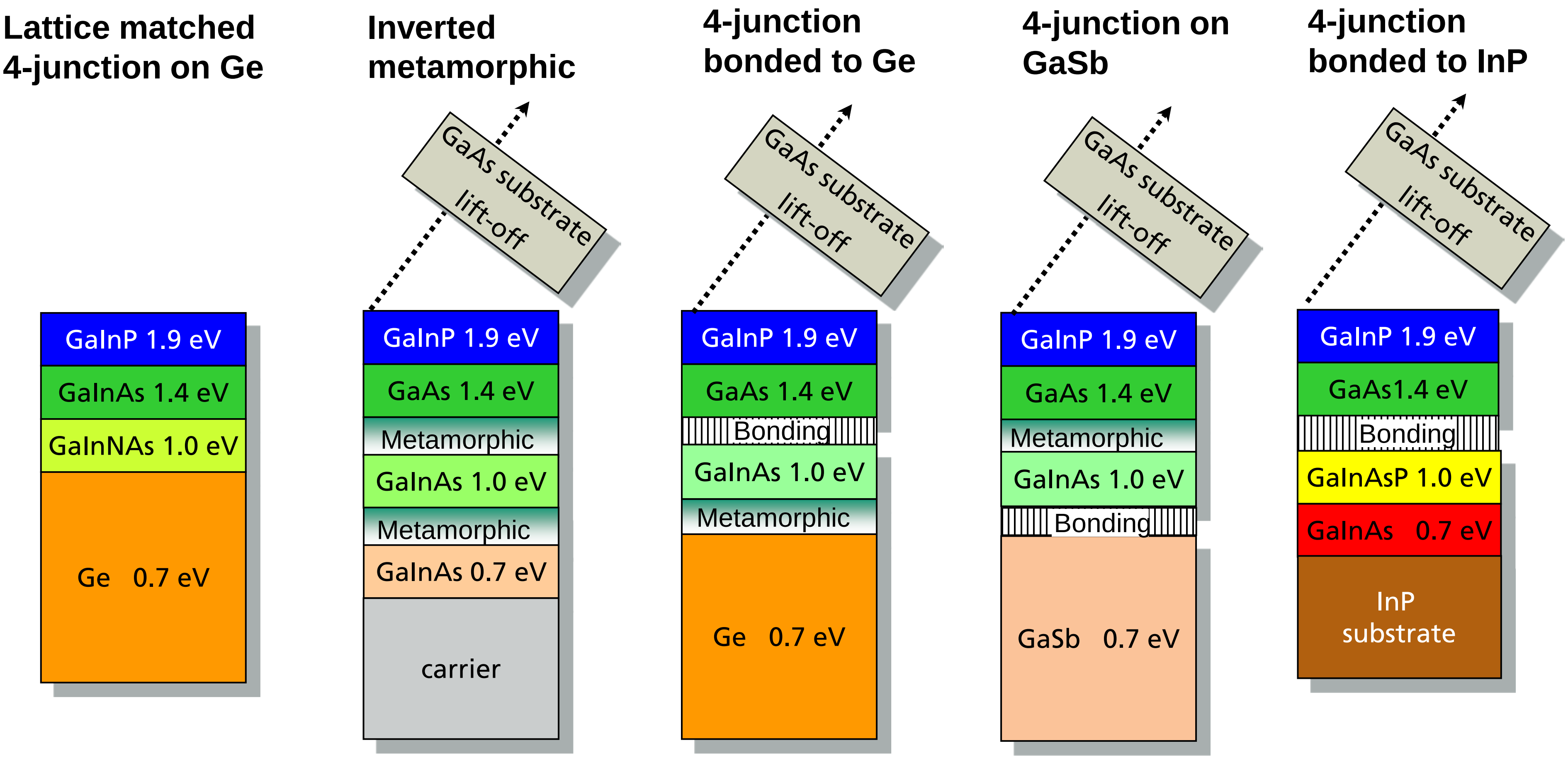
Solar Cell Architectures for 4J Cells with 50 % Efficiency
Developments at Fraunhofer ISE



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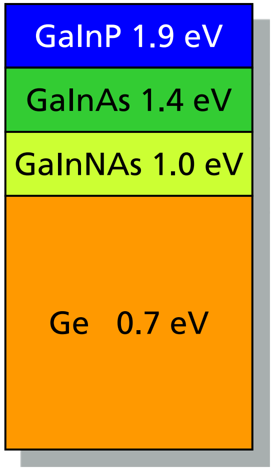
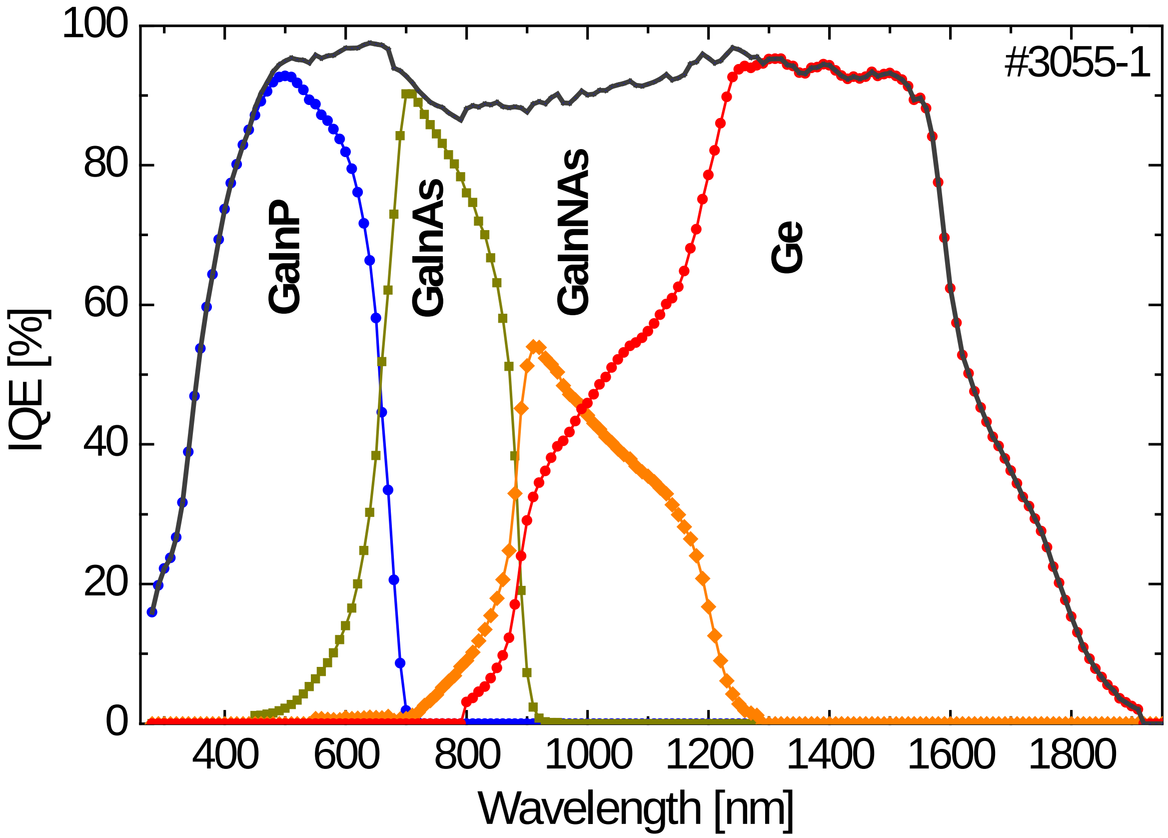
Solar Cell Architectures for 4J Cells with 50 % Efficiency
Developments at Fraunhofer ISE

Lattice matched 4-junction on Ge





Low diffusion length in **MOVPE grown GaInNAs** limits performance !

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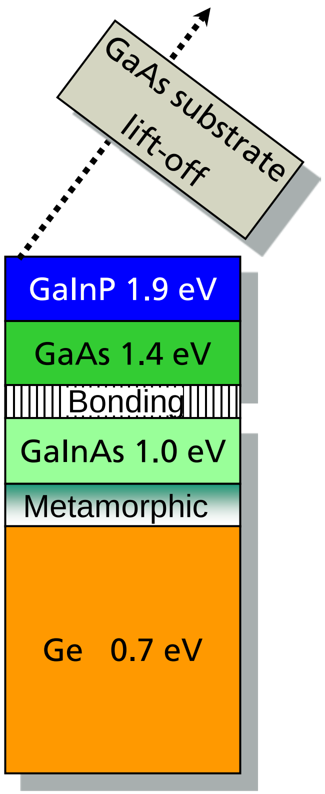
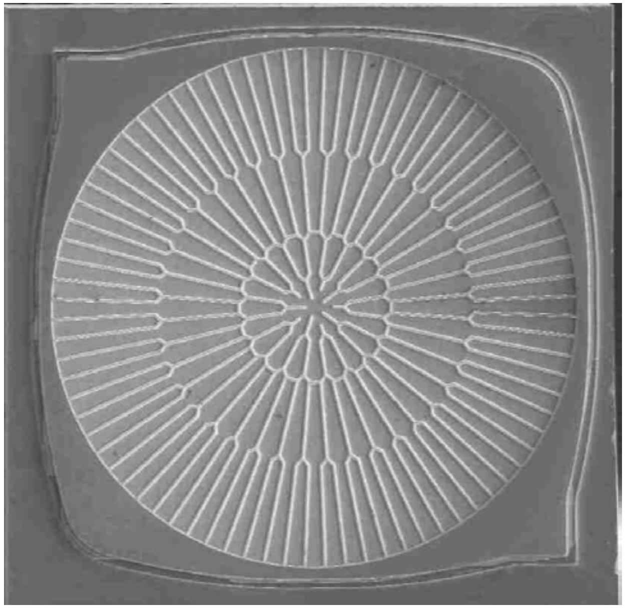
4-Junction Wafer-Bonded Multi-Junction Solar Cell
Ge-based

Technology features

- Inverted growth of top dual-junction cell
- Metamorphic growth in bottom dual-junction cell
- Semiconductor bond

4-junction bonded to Ge





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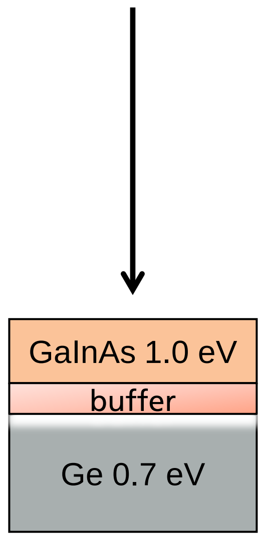
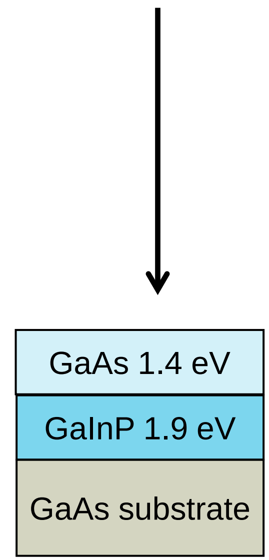
Wafer-Bonded 4-Junction Solar Cell
Ge-based

Metamorphic GaInAs on active Ge

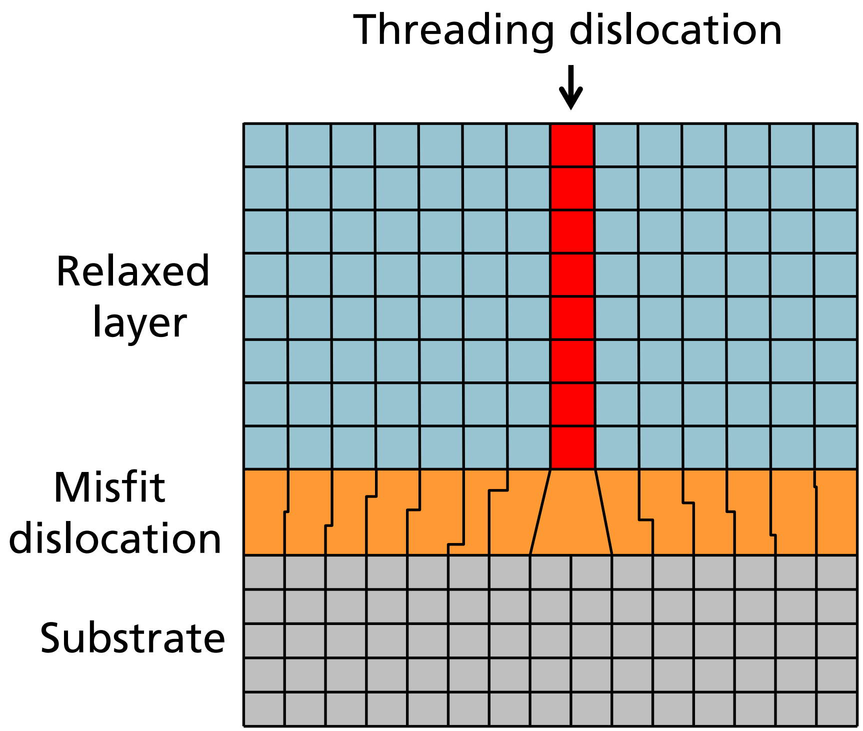


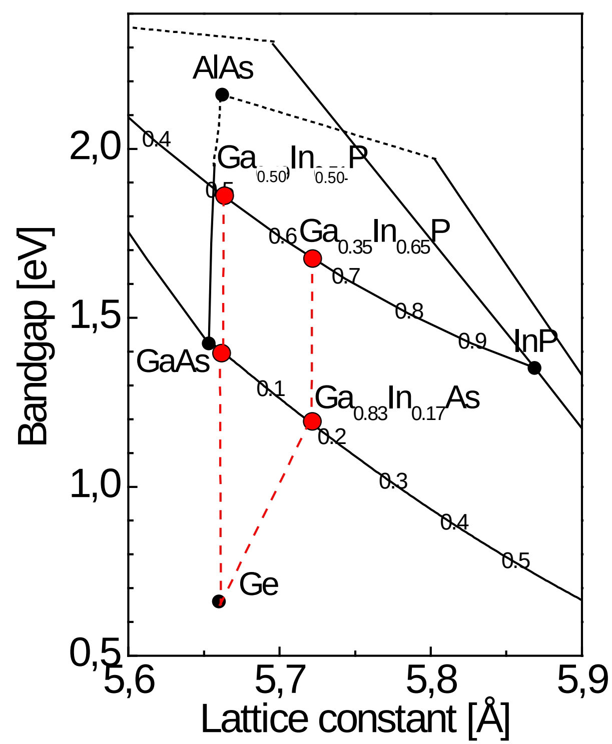
GaAs carrying upper **inverted** dual-junction



Metamorphic Growth of $Ga_{1-x}In_xAs$ on Ge

Control of Threading Dislocations





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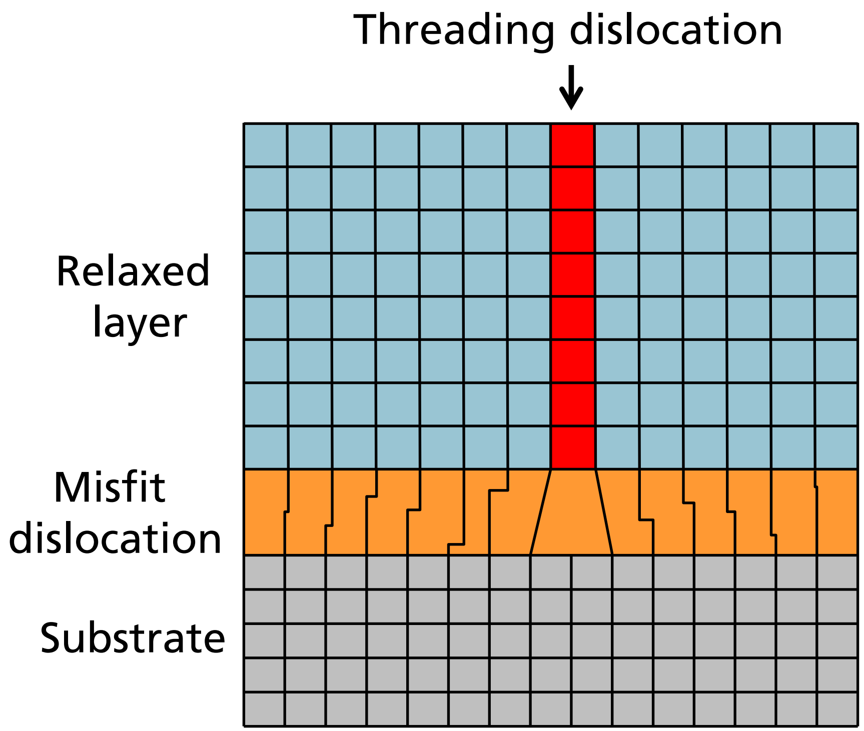
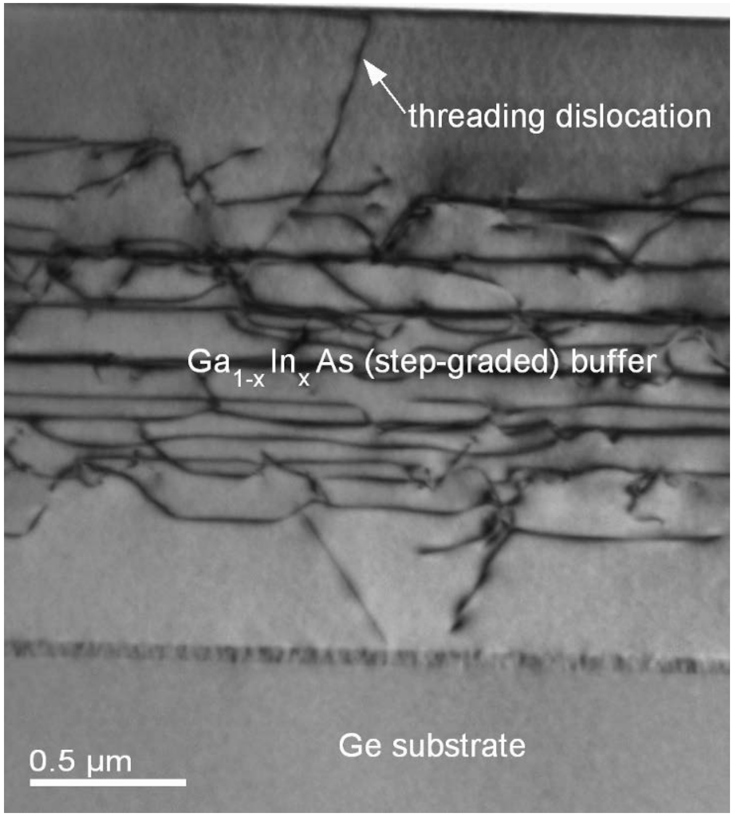
Metamorphic Growth of $Ga_{1-x}In_xAs$ on Ge
Control of Threading Dislocations





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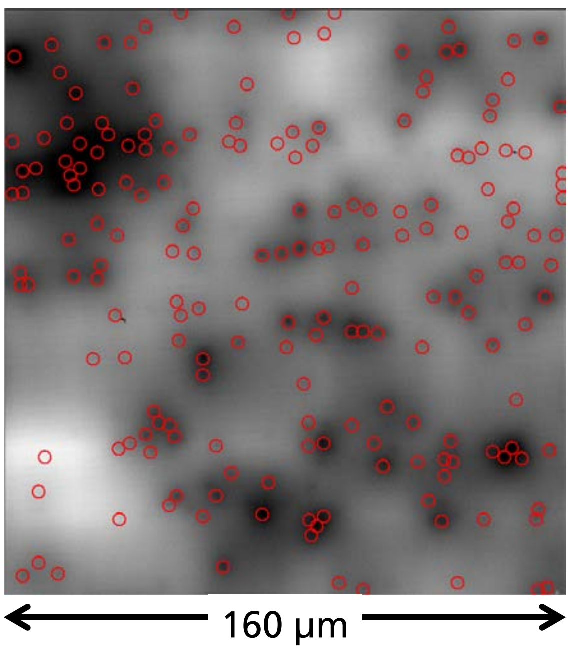
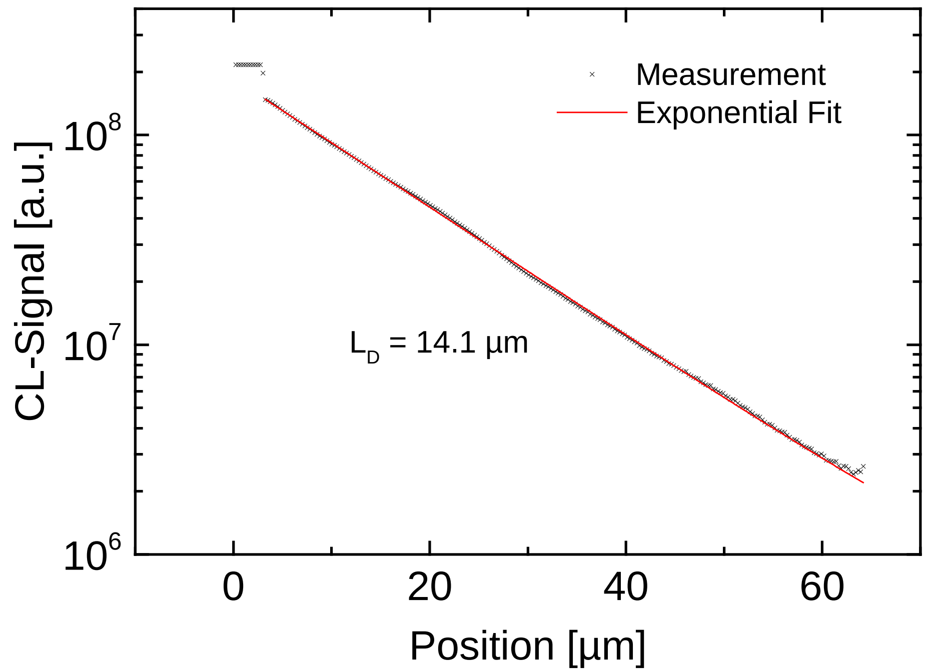
Characterization of $Ga_{0.80}In_{0.20}As$ Sub-Cell Material
Cathodoluminescence Measurements on Test Structures





- threading dislocation density
  TDD = 7.4×10^5 cm^{-2}
- diffusion length in base material
  L_D = 14.1 µm

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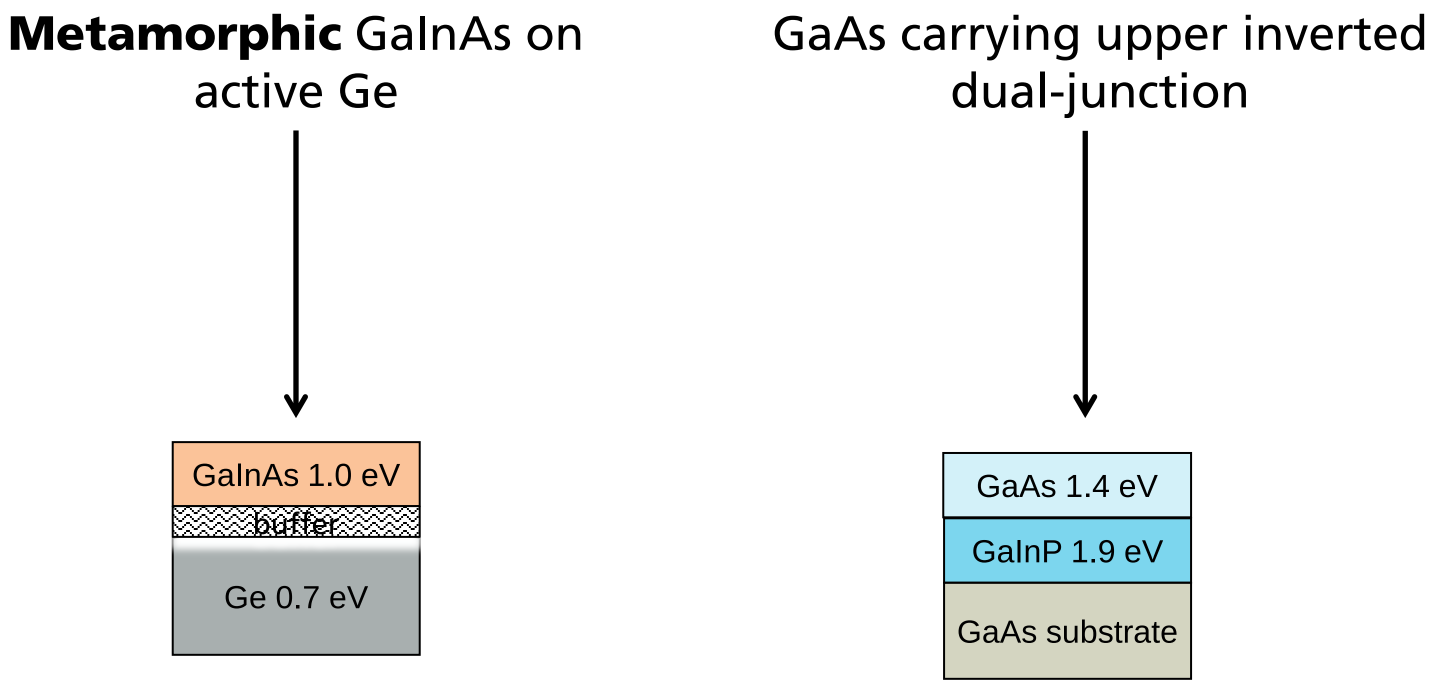
Wafer-Bonded 4-Junction Solar Cell

Ge-based



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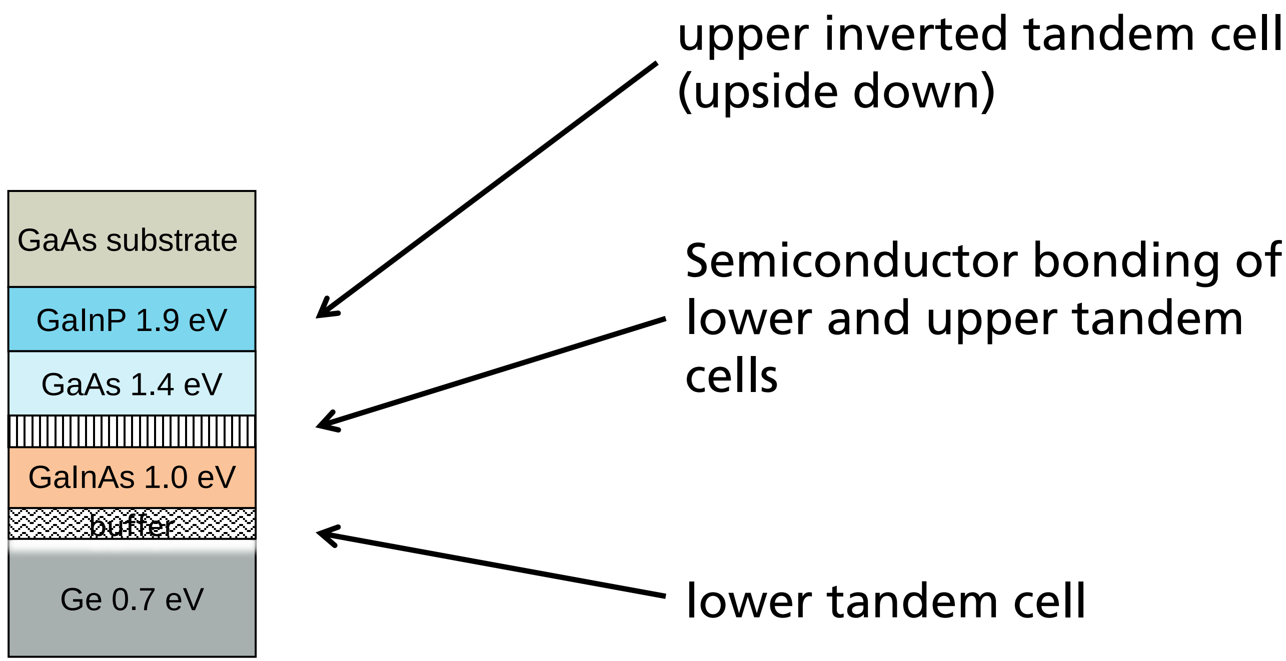
Wafer-Bonded 4-Junction Solar Cell

Ge-based



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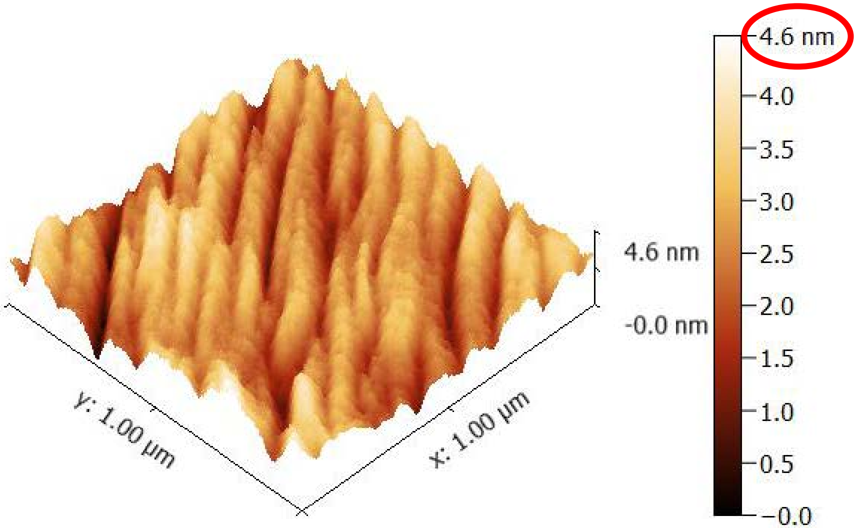
Ge-based 4-Junction Solar Cell
Bonding Interface

Metamorphic surface after epitaxy

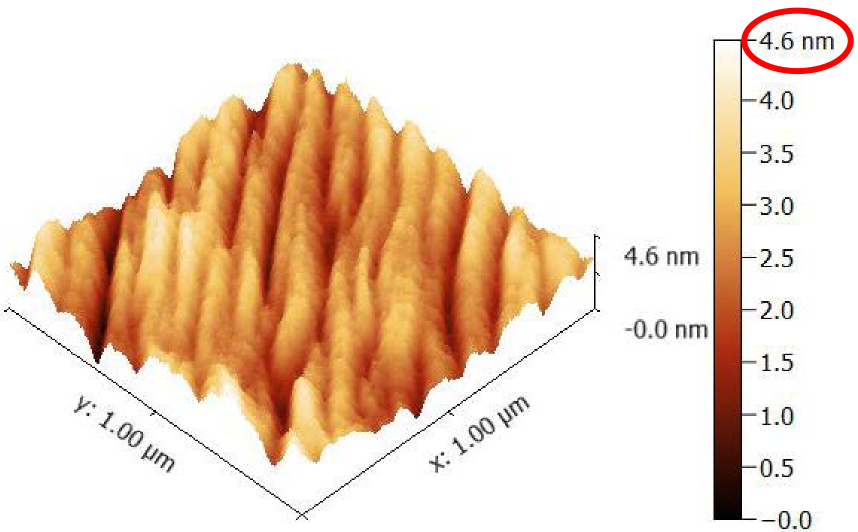


Roughness <1nm required for successful bonding!

Ge-based 4-Junction Solar Cell

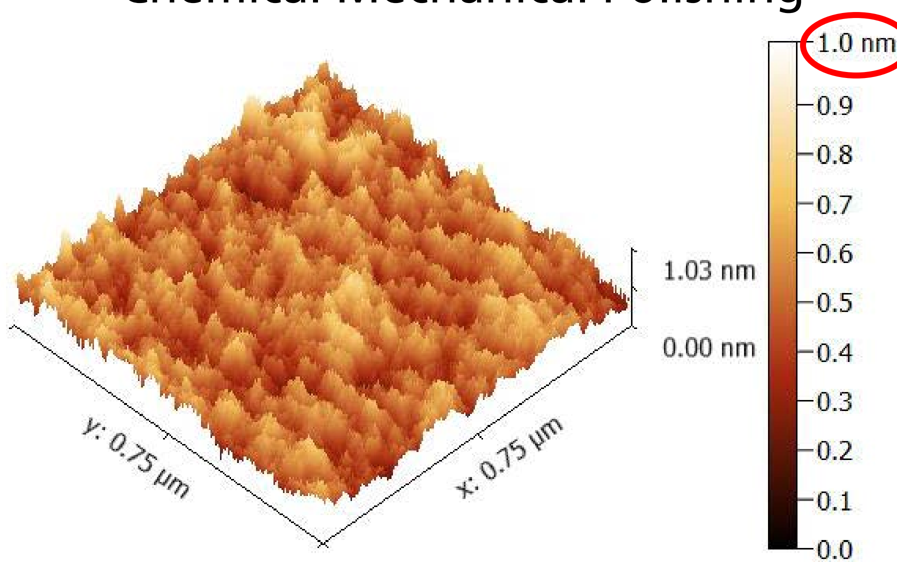
Bonding Interface

Metamorphic surface after epitaxy



Surface after

Chemical Mechanical Polishing



→ Roughness <1nm required for successful bonding!

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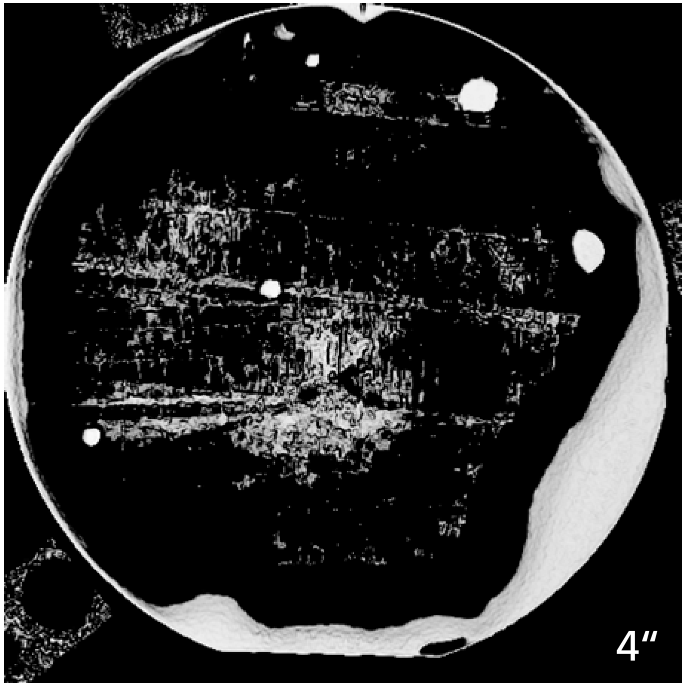
Ge-based 4-Junction Solar Cell

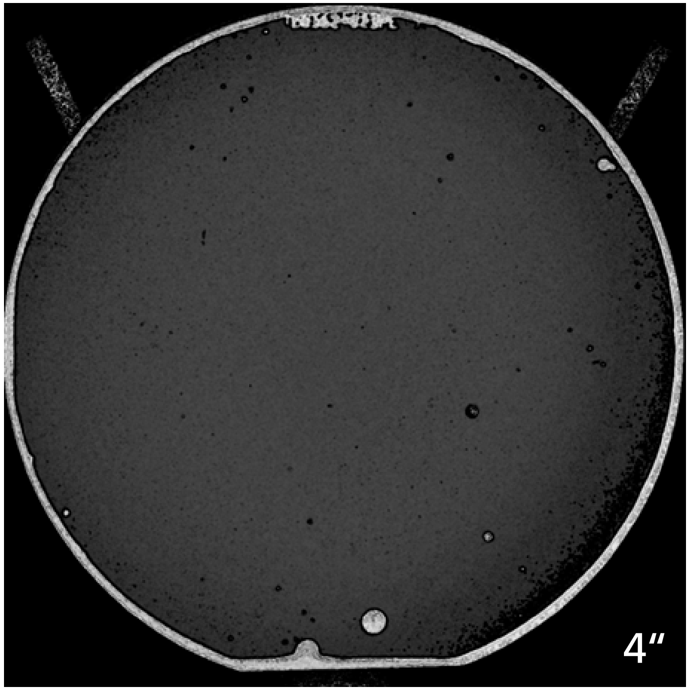
Bonding Interface

Scanning Acoustic Microscope Images of Interface

Before optimization



After optimization



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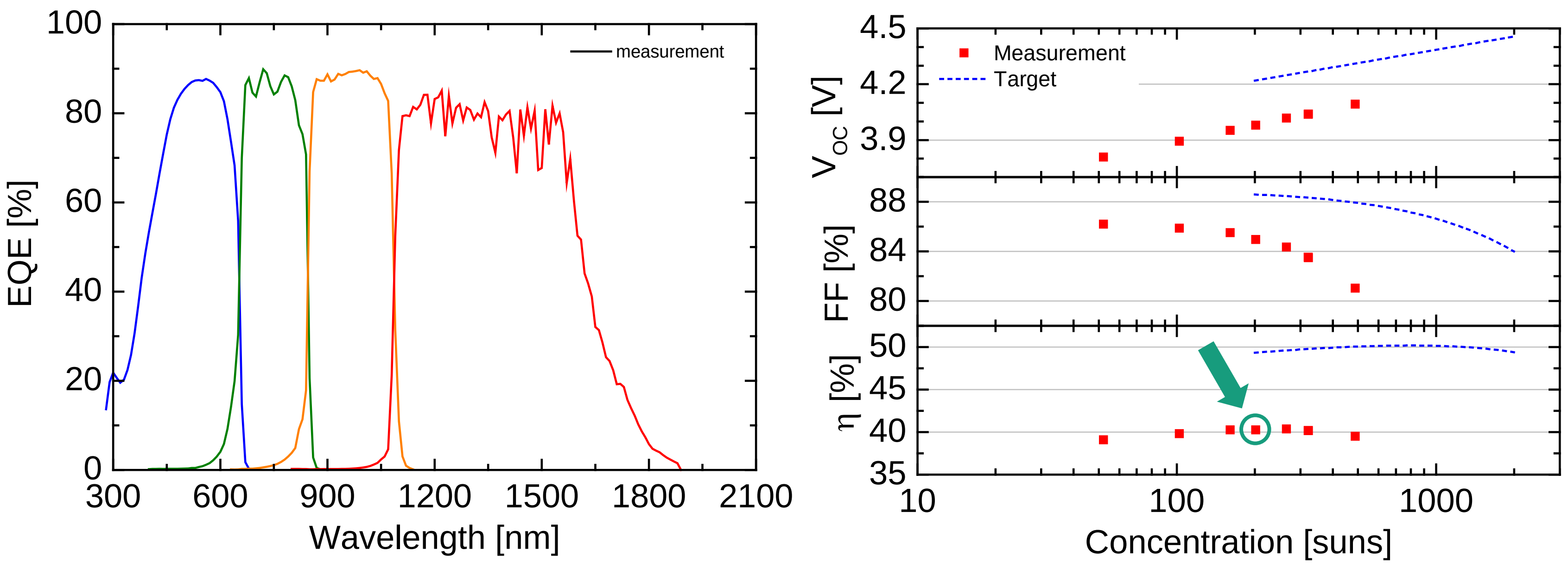
Wafer-Bonded 4-Junction Solar Cell
Ge-based

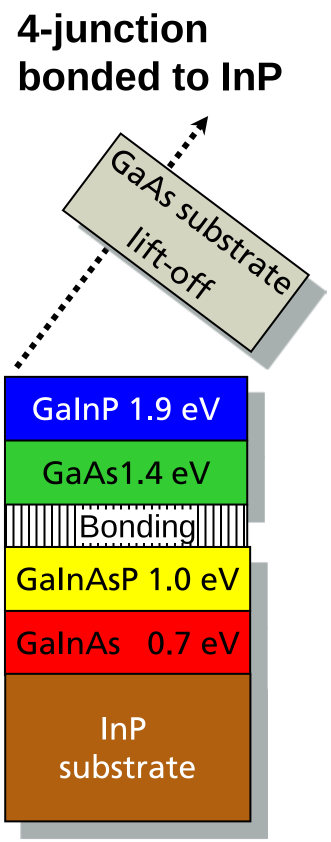


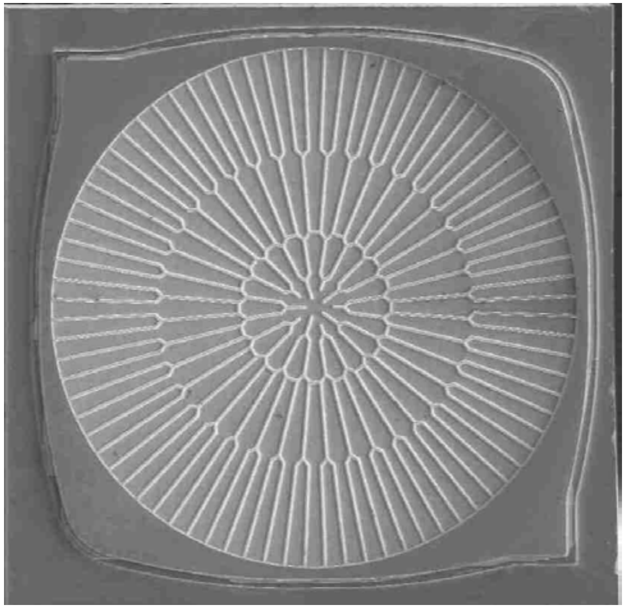
→ Currently best efficiency reached: 40.3% @ 203 suns

4-Junction Wafer-Bonded Multi-Junction Solar Cell
InP-based

Technology features

- Inverted growth of top dual-junction cell
- Lattice matched growth on InP for bottom dual-junction cell
- Semiconductor bond





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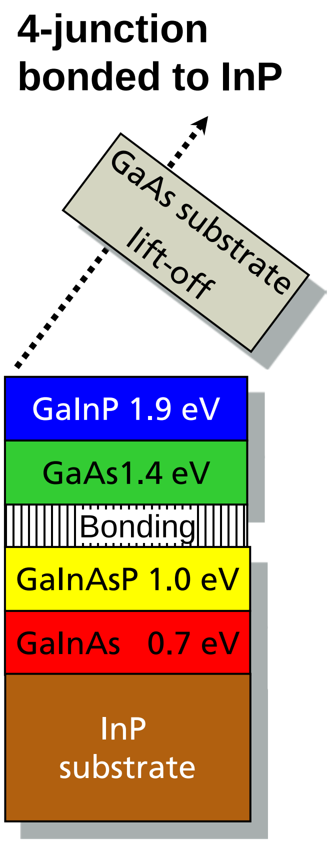
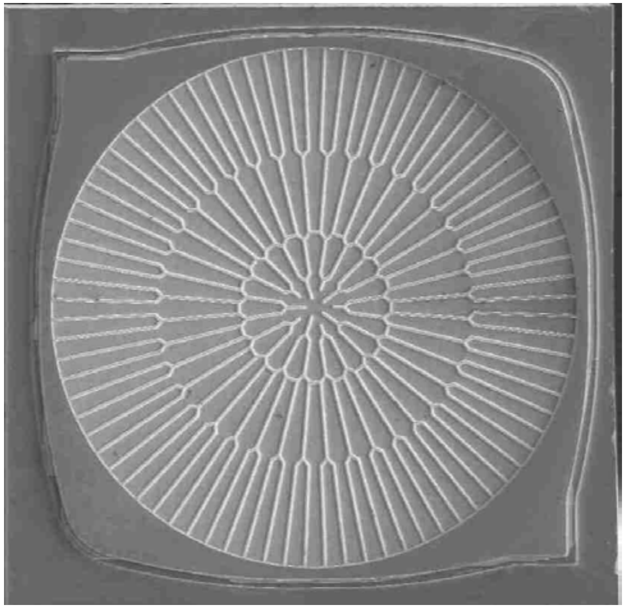
4-Junction Wafer-Bonded Multi-Junction Solar Cell
InP-based

Technology features

- Inverted growth of top dual-junction cell
- Lattice matched growth on InP for bottom dual-junction cell
- Semiconductor bond

→ InP substrate too costly!





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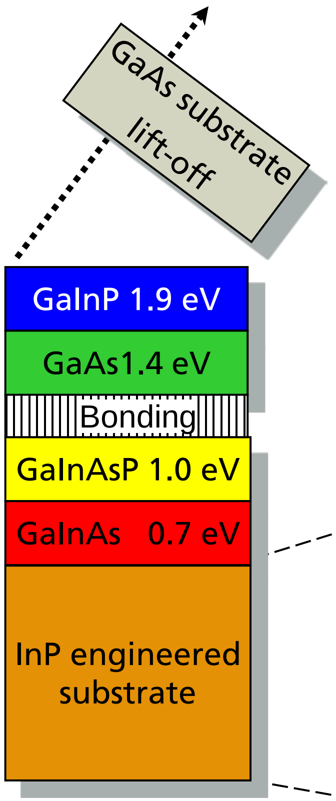
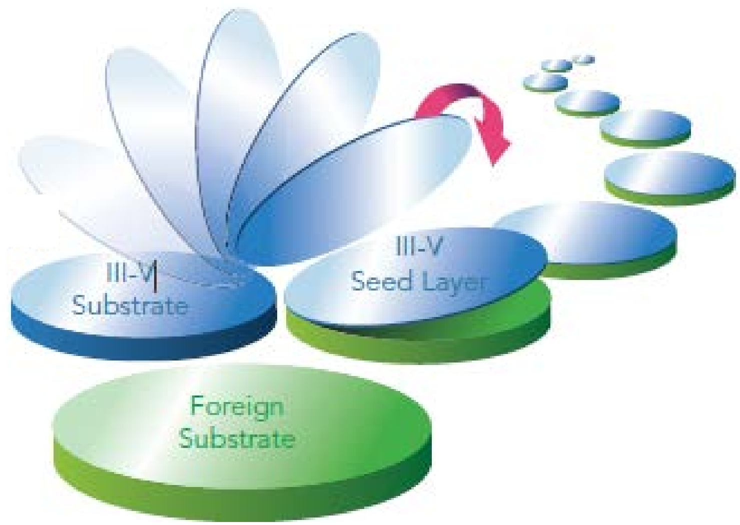
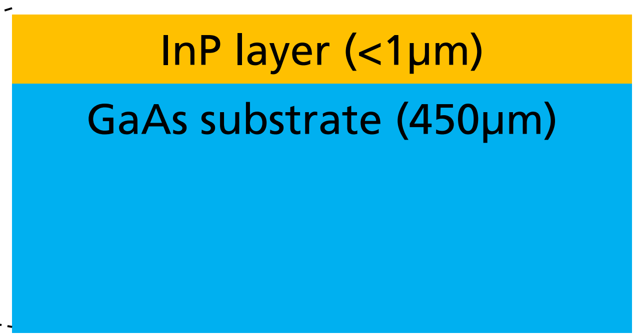
Engineered Substrate from Soitec

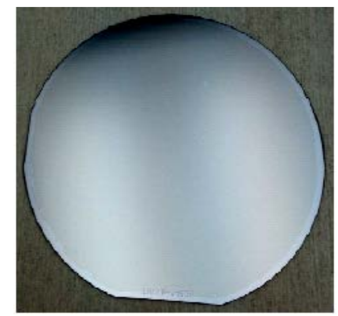
4-junction bonded to InP



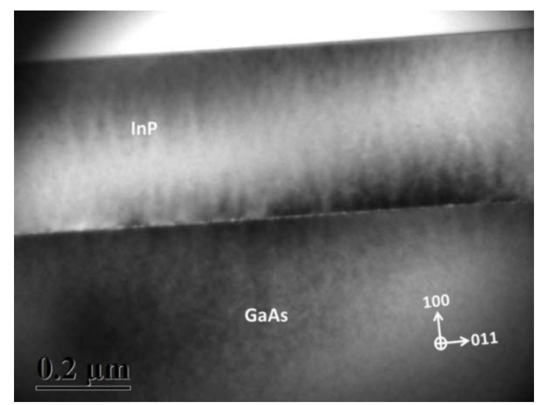


Six InP refresh cycles demonstrated



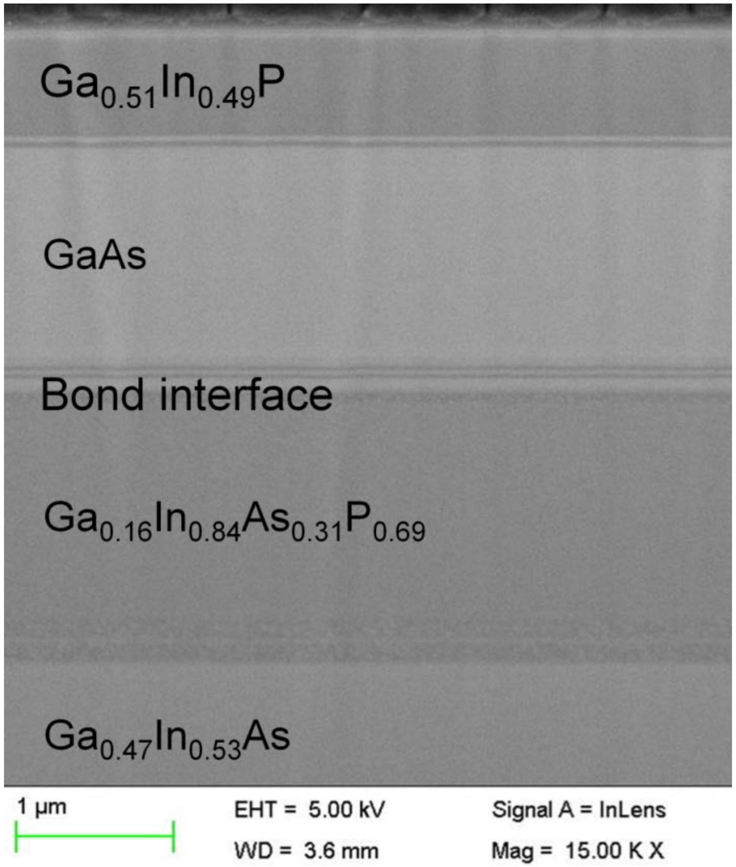


InP-On-GaAs

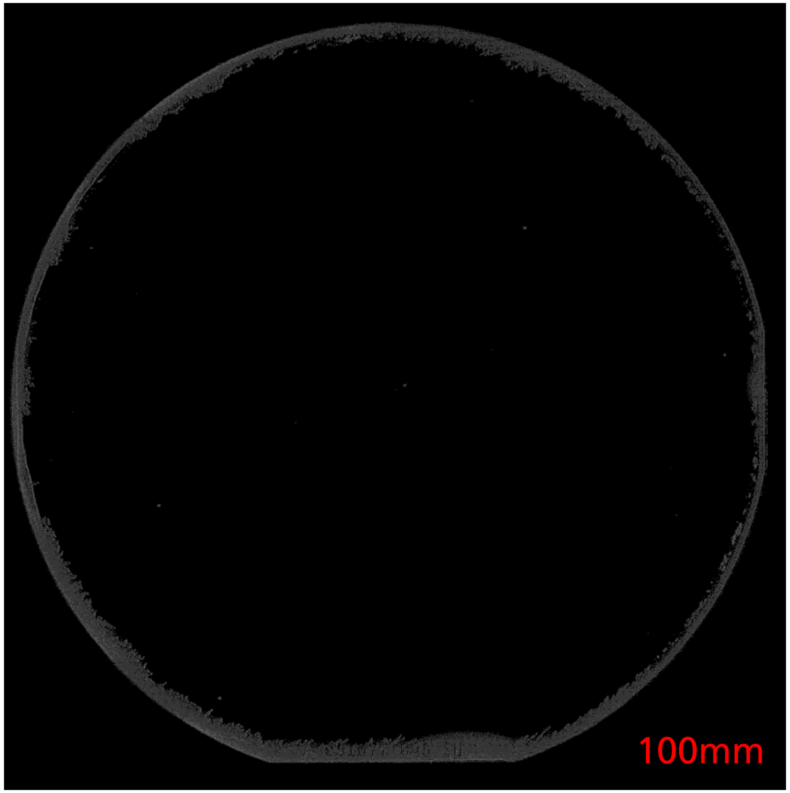


Wafer-Bonded 4-Junction Solar Cell

scanning electron microscopic picture



scanning acoustic microscopic picture

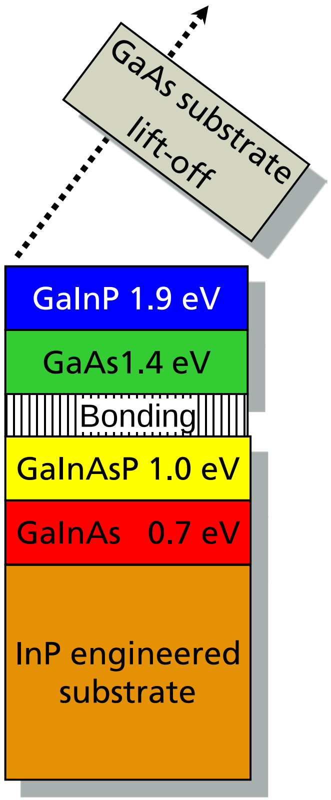


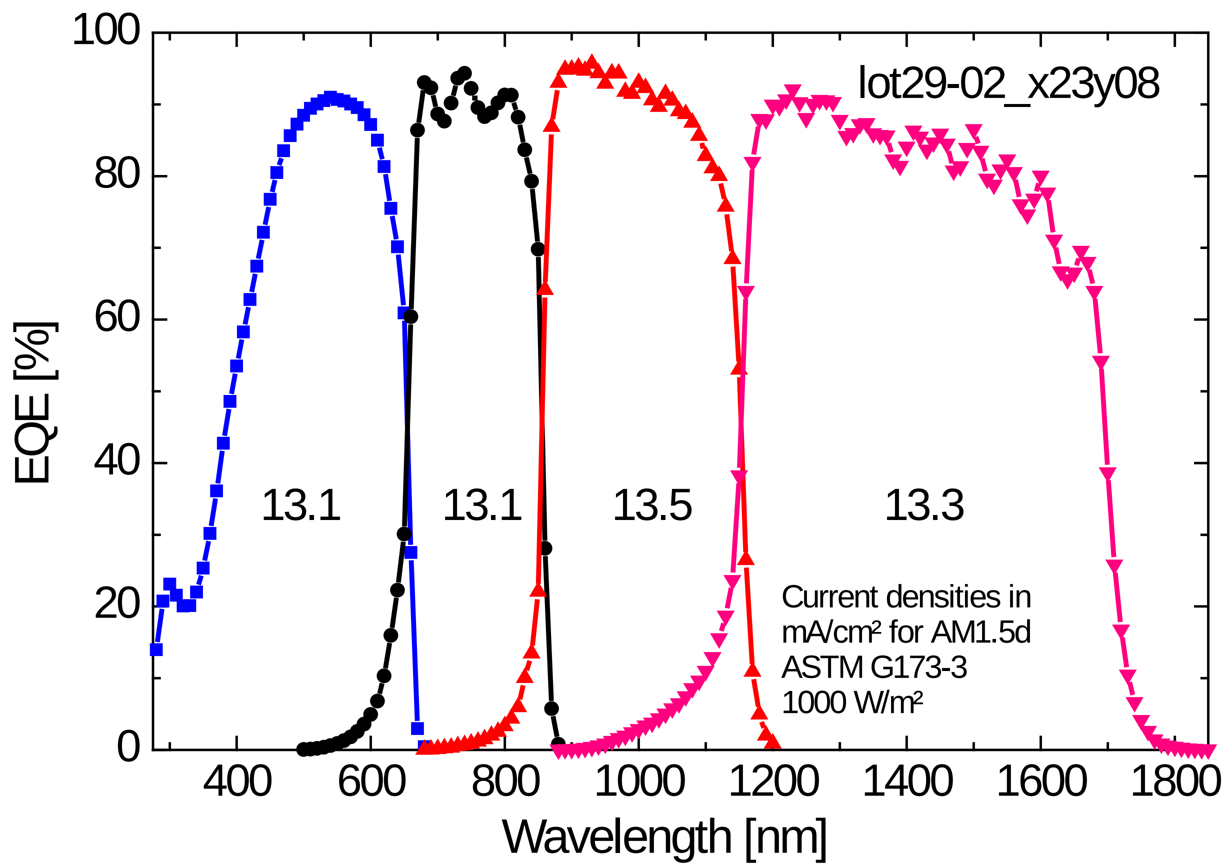
Bonding performed at CEA Leti or Soitec

F. Dimroth et al., Progress in PV 22(3), 277 (2014)

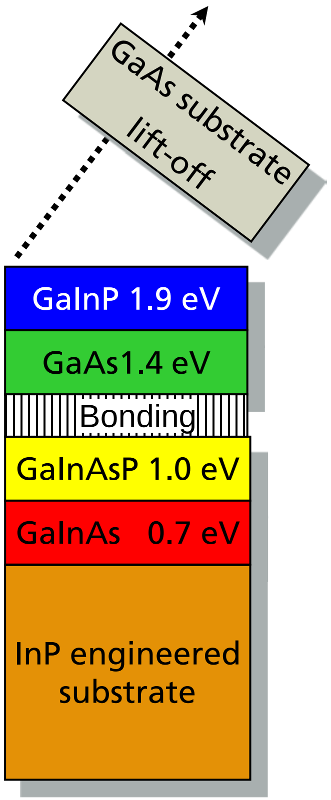
Soitec cea leti Fraunhofer ISE

InP based 4-Junction Solar Cell Results on Engineered Substrate

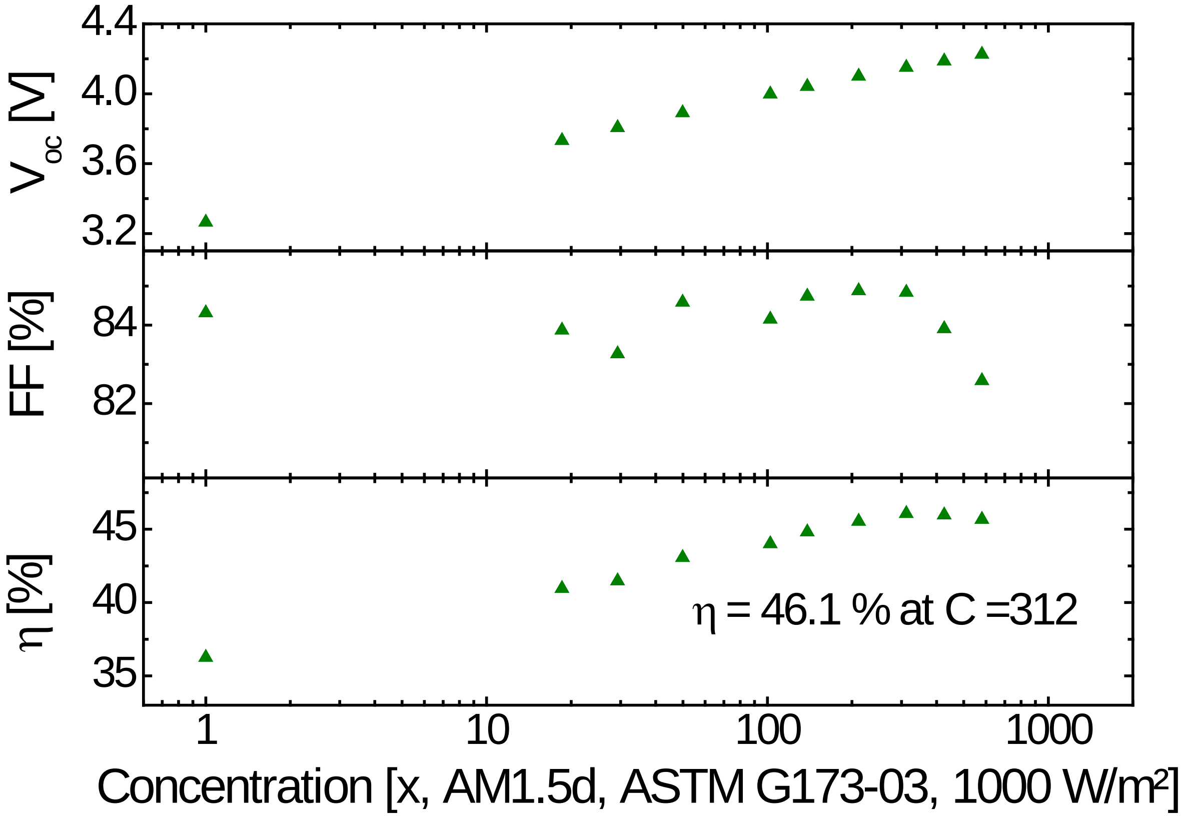




InP based 4-Junction Solar Cell Results on Engineered Substrate

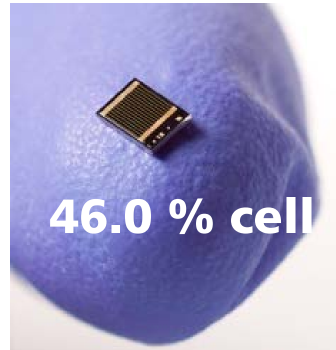


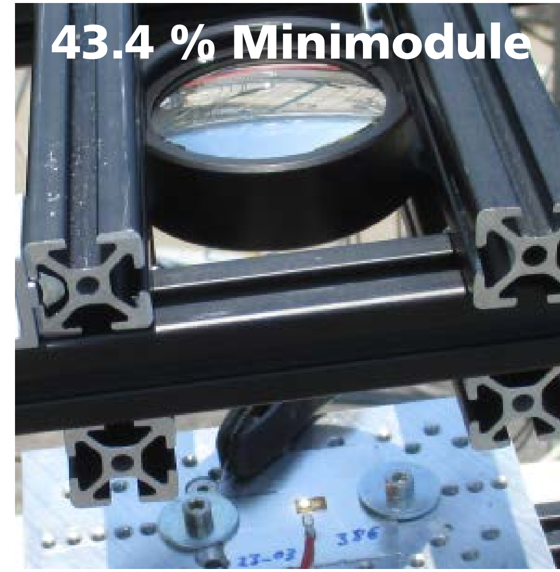
η = **46.1 %** C = 312



Soitec cea leti Fraunhofer ISE

Effciency Tables





Progress in
PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2016; **24**:3–11
Published online 24 November 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2728

M. A. Green *et al.* Solar cell efficiency tables

Table IV. Terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct beam AM1.5 spectrum at a cell temperature of 25°C.

Classification	Effic. (%)	Area (cm^2)	Intensity[a] (suns)	Test centre (date)	Description
Single cells					
GaAs	29.1 ± 1.3[b]	0.0505 (da)	117	FhG-ISE (3/10)	Fraunhofer ISE
Si	27.6 ± 1.2[d]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact [46]
CIGS (thin-film)	23.3 ± 1.2[b]	0.09902 (ap)	15	NREL (3/14)	NREL [47]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE bonded [48]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[b]	0.09709 (da)	234	NREL (9/14)	NREL, 4J monolithic [49]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, inverted metamorphic [50]
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs	**43.4 ± 2.4[b]**	**18.2 (ap)**	**340[j]**	**FhG-ISE (7/15)**	**Fraunhofer ISE (lens/cell) [13]**
Submodule					
GaInP/GaInAs/Ge; Si	40.4 ± 2.8[i]	287 (ap)	365[j]	NREL (11/14)	UNSW split spectrum [51]
Modules					
Si	20.5 ± 0.8[b]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells) [52]
Three junction	35.9 ± 1.8[l]	1092 (ap)	N/A	NREL (8/13)	Amonix [53]
Four junction	38.9 ± 2.5[m]	812.3 (ap)	333	FhG-ISE (4/15)	**Soitec [14]**

38.9 % Module

Thanks to the Fraunhofer ISE
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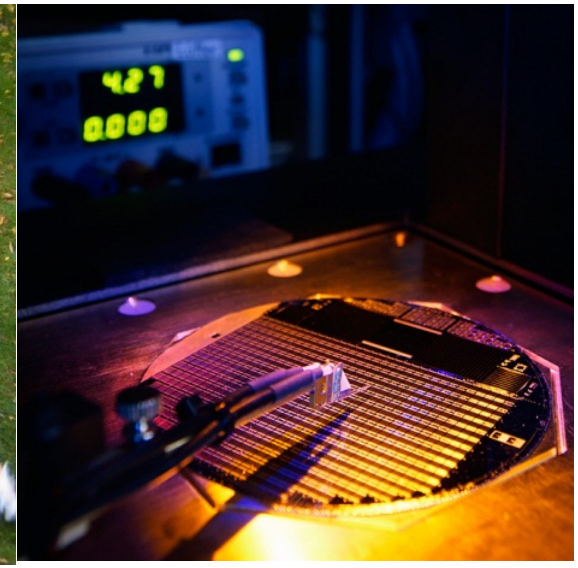

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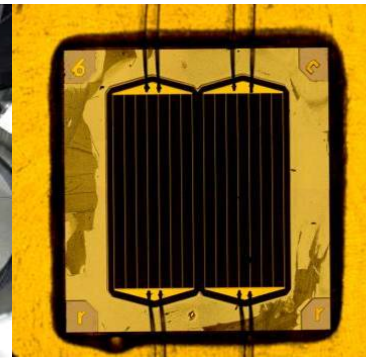
Thank You for Your Attention!





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