New Materials and Designs for Advanced Solar Cells

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Outline

1. Progress with solar cell efficiency (one sun, no CPV)
2. Where and how to go further in terms of efficiency?
3. What is new with tandems?
4. Other approaches for more efficient and affordable solar cells

General remarks

1. More than 90 % of solar cells produced globally are made of crystalline silicon (c-Si). Mature concepts in terms of cell design, including PERC, are predominantly used in c-Si cell manufacturing.

2. Progress with techno-economic parameters of c-Si cells can be expected mainly due to innovative manufacturing processes (e.g. novel contact printing technologies, high-throughput growth of wafers, smart evaluation of PV materials, efficient quality control, etc.), rather than cell efficiency.

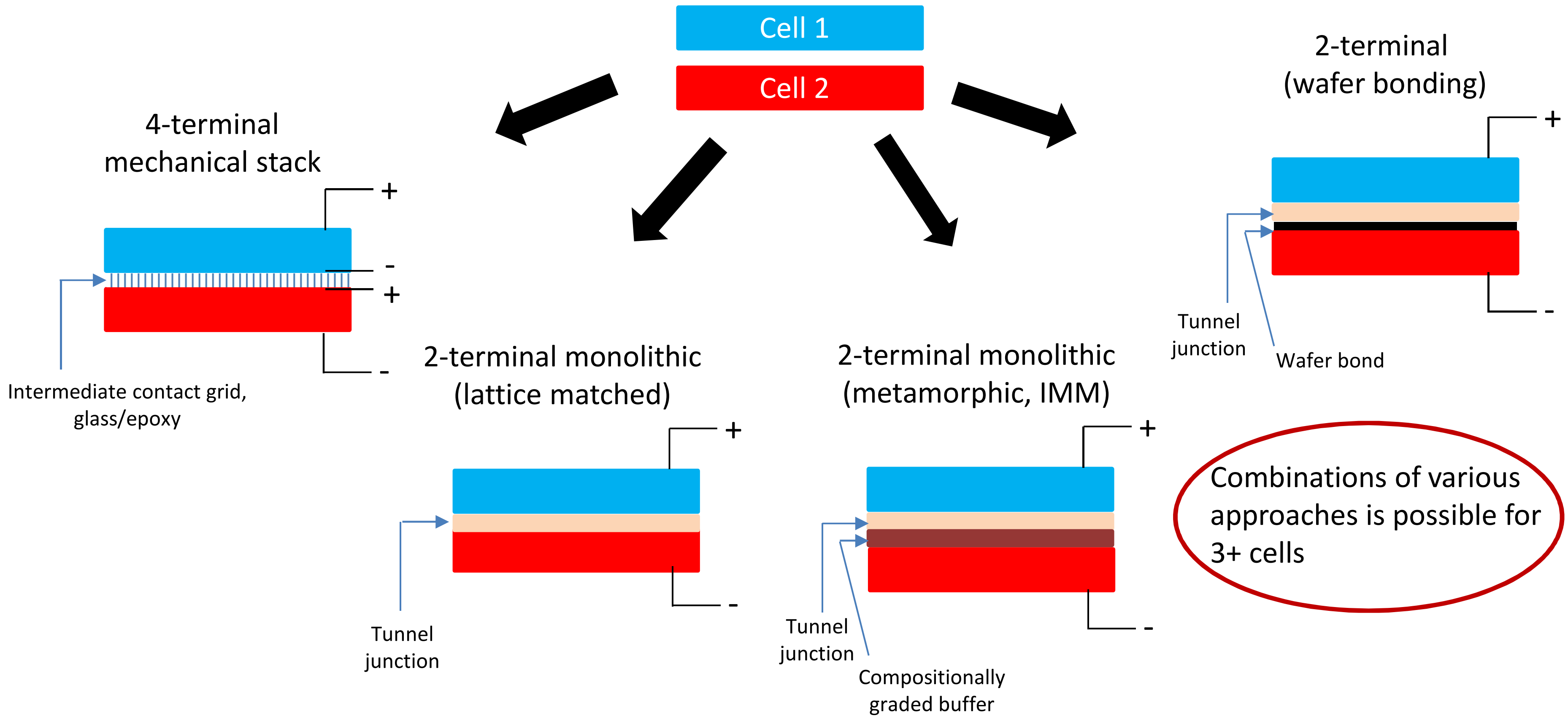
Progress with single-junction cells

	Efficiency, %	Jsc, mA/cm^2	Voc, V	FF, %	
		Si cells			
UNSW	**25**	42.7	0.706	82.8	1999
Kaneka	**26.7**	42.65	0.738	84.9	2017
Rel. improvement	6.8%				0.38%/year
		III-V cells			
Alta Devices	**28.8**	29.68	1.122	86.5	2012
Alta Devices	**29.1**	29.78	1.1272	86.7	2018
Rel. improvement	*1.04%*				0.17%/year

- **Progress with single-junction cell efficiency is steady but slow**
- **Tandem solar cells, including those with Si sub-cells, is a promising way to increase solar cell efficiency**

Tandem solar cells

Tandem PV is a relatively straightforward idea: 1980's, monolithic GaAs-based at NREL, mechanically stacked GaAs-GaSb at Boeing. A crucial prerequisite for tandem cell/module commercialization is the necessity for top and bottom tandem sub-cells to be similar in cost, efficiency, and long-term performance.



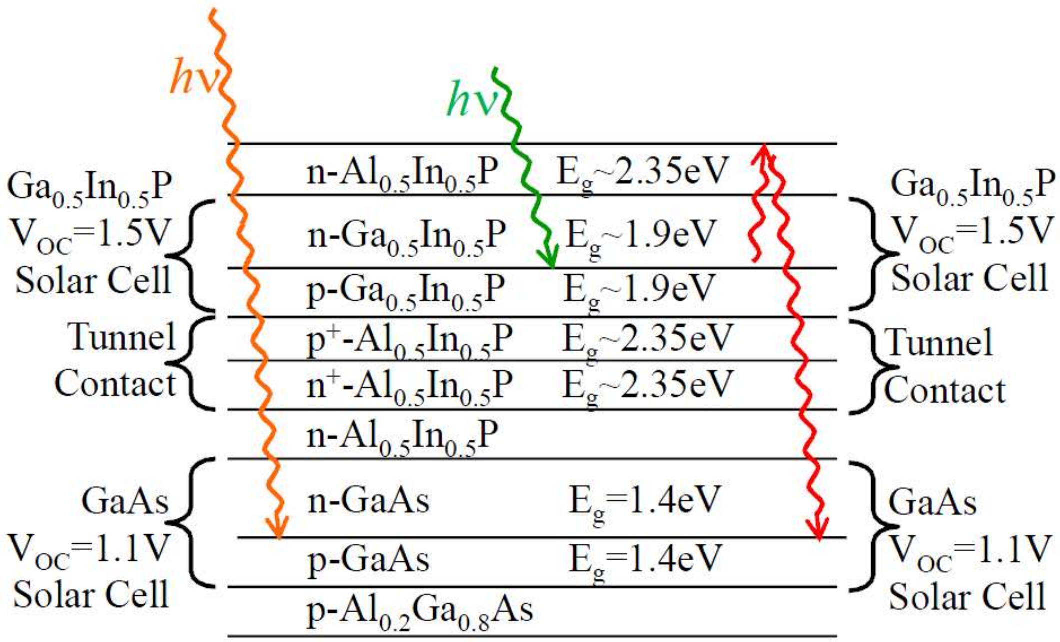
Combinations of various approaches is possible for 3+ cells

Advances in innovative technologies offer a new potential for more efficient and affordable tandems

Lattice-matched tandem solar cells

https://bapvc.stanford.edu/
October 2014 BAPVC meeting

Alta Devices:



Bandgap-voltage offset
$W_{OC} = E_g/q - V_{OC}$

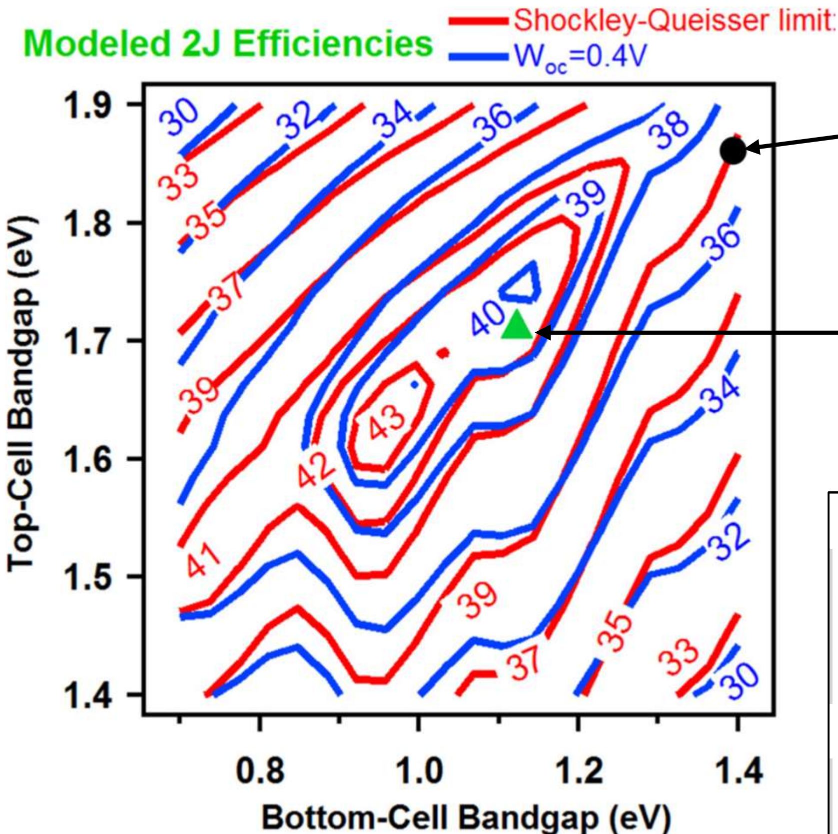
~ 0.36V

~ 0.31V

- **34% (one sun AM1.5G) should be possible under realistic assumptions**
- **Achieved so far: 32.8% (LG), 31.6% (Alta Devices)**
- **Reuse of GaAs substrates via epitaxial liftoff (ELO)**

https://doi.org/10.1063/1.5008517

Choice of Cells for Monolithic Tandems



1.86 eV/1.41 eV; W_{oc} = 0.36V and 0.31V
lattice-matched $Ga_{0.5}In_{0.5}P$/GaAs
LG, Alta Devices

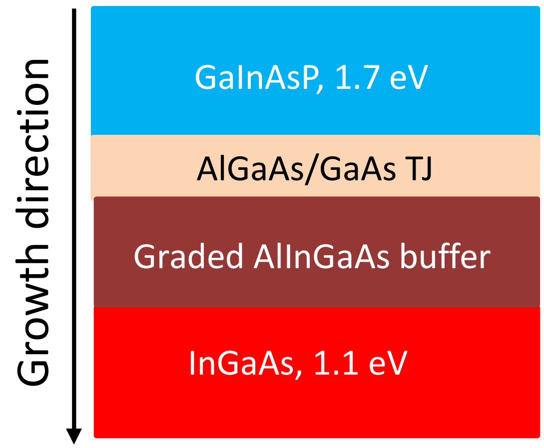
1.7 eV/1.1 eV; W_{oc} = 0.39V for both cells
GaInAsP lattice-matched to GaAs / InGaAs lattice-mismatched
NREL (2018)

	Eff. %	Jsc, mA/cm2	Voc, V	FF, %	
	Lattice matched 2-junction GaInP-GaAs				
LG	32.8	14.56	2.568	87.7	2018
	Inverted metamorph (IMM) InGaAsP-InGaAs				
NREL	32.6	19.51	2.024	82.5	2018

- **Lattice-matched 2J cells exceed 2J IMM so far**
- **Despite the remarkable efficiency achieved in InGaAsP/InGaAs cells, potential advantages of 2J IMM cells are not fully used yet (this is good)**

Remarks on metamorphic layers

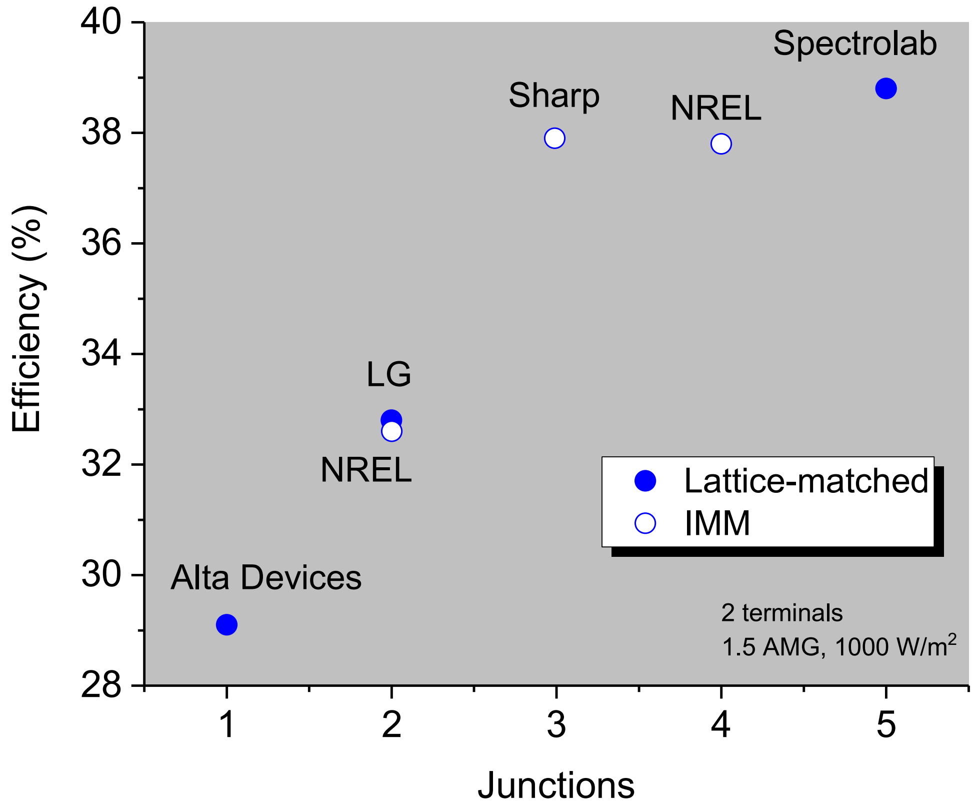
- An obvious way to increase flexibility in cell design but success is not overwhelming
- Inverted (IMM) approach helps: less defects in the most parts of solar cells
- Problem: in metamorphic cells bandgap-voltage offsets are generally higher due to a higher defect density



- Buffer layers are pretty complex but not perfect. A lot of fine tuning with regards to buffer structure and process parameters is necessary. Very slow epitaxial growth is required.
- All defects interact and somehow connected. No clear picture yet. A systematic study could be helpful.

- More advantages for concentrator cells than one-sun cells due to higher current densities (defect saturation). However, the best results (46% at ≈500 suns) were achieved at Soitec/Fraunhofer via bonding of lattice matched tandems (2J on GaAs + 2J on InP)
- On the other hand, Microlink is working on commercialization of IMM cells (currently 3 junctions, plans up to 6)

More subcells/junctions



3J Sharp: 1.8/1.41/0.98 (IMM)

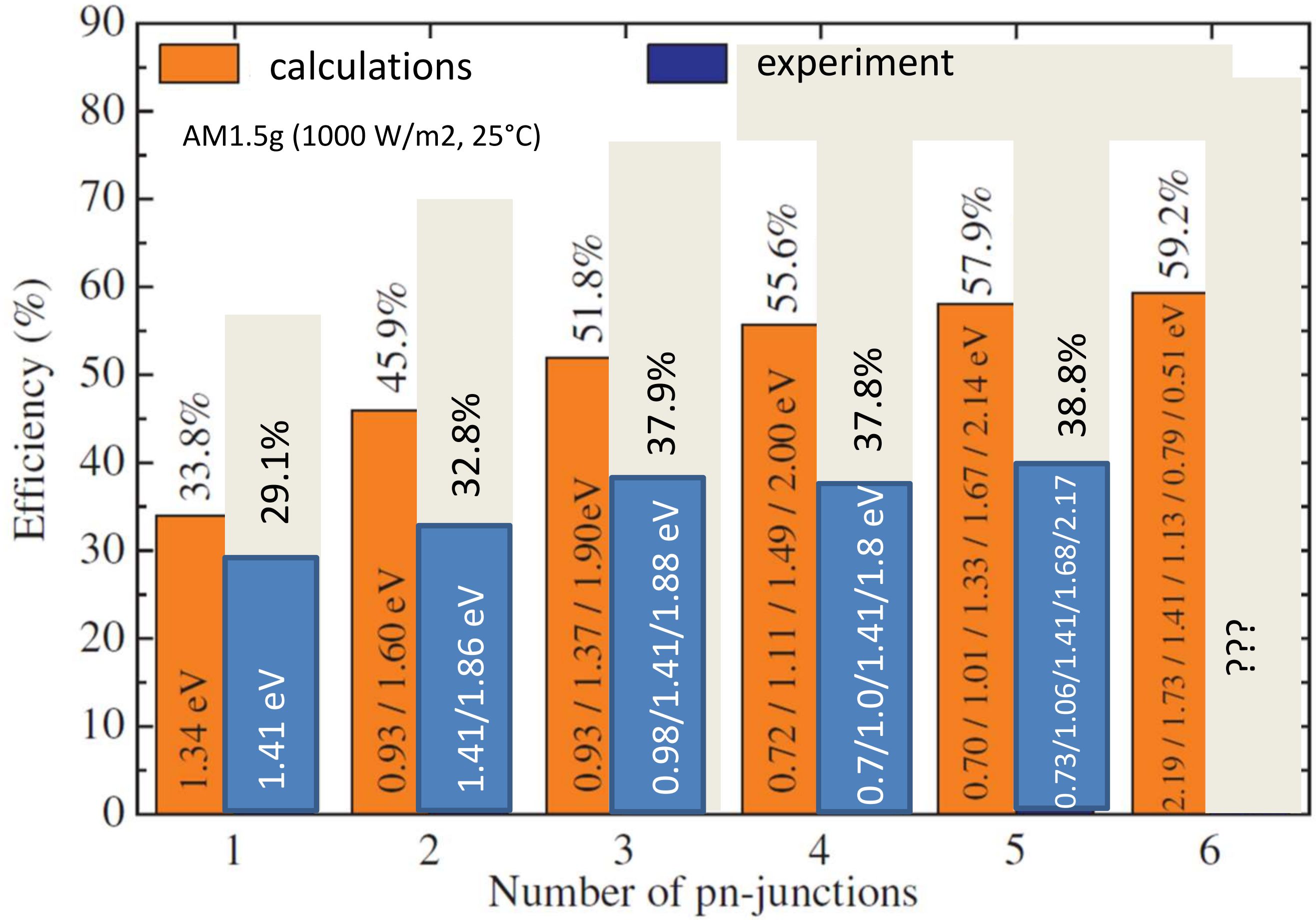
4J NREL: 1.8/1.41/1.0/0.7

5J Spectrolab: bonded 2.17/1.68/1.41 + 1.06/0.73 eV

- **IMM cells show clear advantages but no absolute record so far**
- **37.8% 3J GaInP/GaAs/InGaAs IMM cell with epitaxial liftoff**
- **NREL is working on 6J devices but no efficiency data yet**

Efficiency calculations vs. reality

FhG ISE calculations
Adv. Opt. Techn. 2014; 3(5-6): 469–478

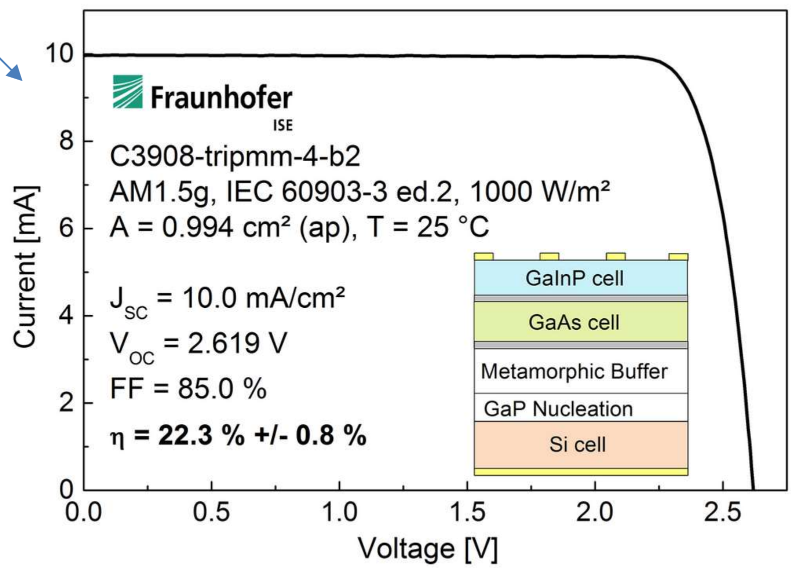


- **The fight for efficiency is tough**

MJ III-V on Si wafers

Silicon is a major candidate for tandems: suitable band gap, relatively low price, established material in PV industry

3J GaInP/GaAs/Si: 35.9%, mechanical stack, 4-terminal (2017), NREL
2J GaAs/Si: 32.8%, mechanical stack, 4-terminal (2017), NREL
3J GaInP/GaAs/Si: 22.3%, monolithic, 2-terminal (2019), FhG ISE

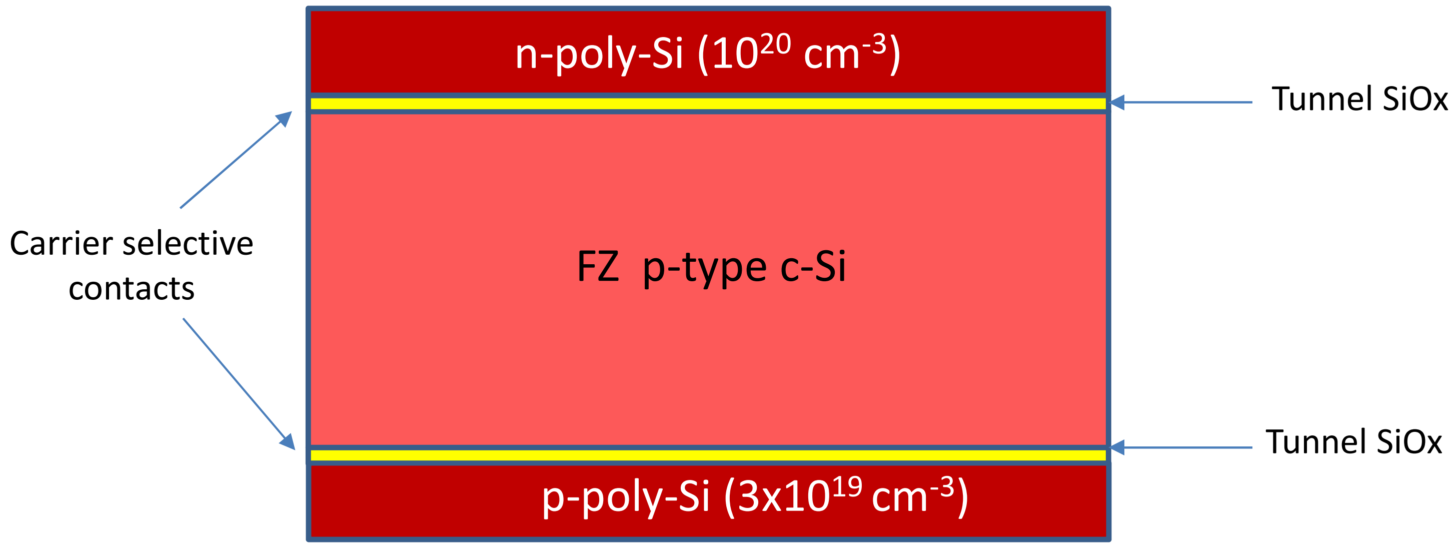


https://www.ise.fraunhofer.de/en/press-media/press-releases/2019/photovoltaic-trend-tandem-solar-cells-record-efficiency-for-silicon-based-multi-junction-solar-cell.html

3J GaInP/GaAs/Si: 33.3%, wafer bonded, 2-terminal (2017), FhG ISE

Advanced c-Si cell: Tunnel Oxide Passivated Contact - TOPCon

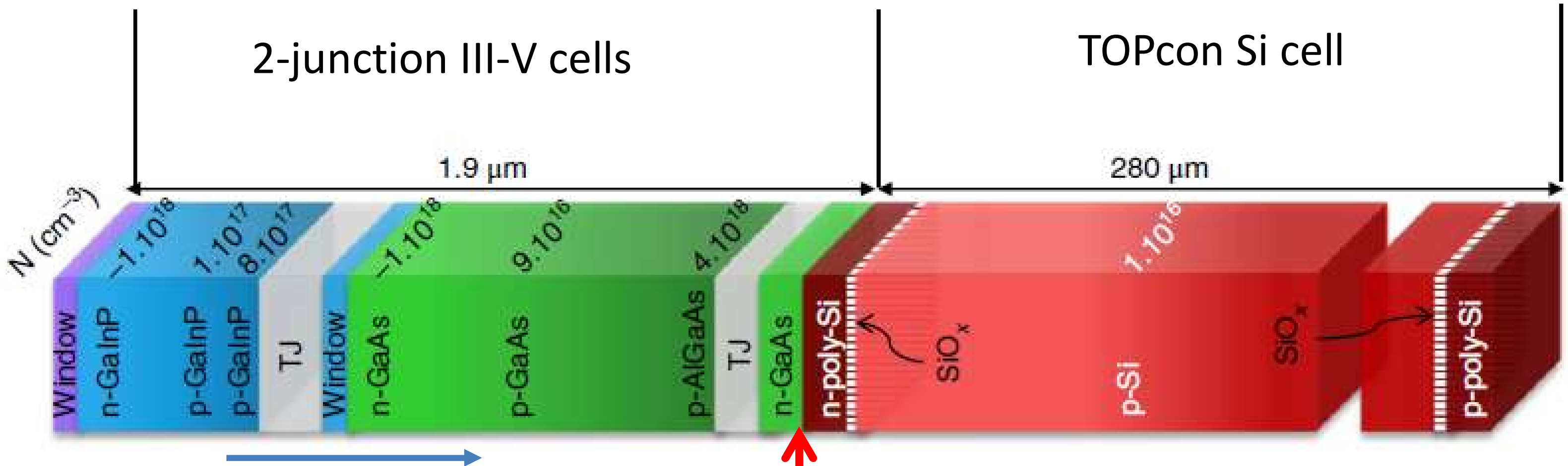
Fraunhofer ISE



- **Cells (25.8% eff.) are similar to heterojunction HIT solar cells (with a-Si) but allow higher temperature of post-manufacturing processing**

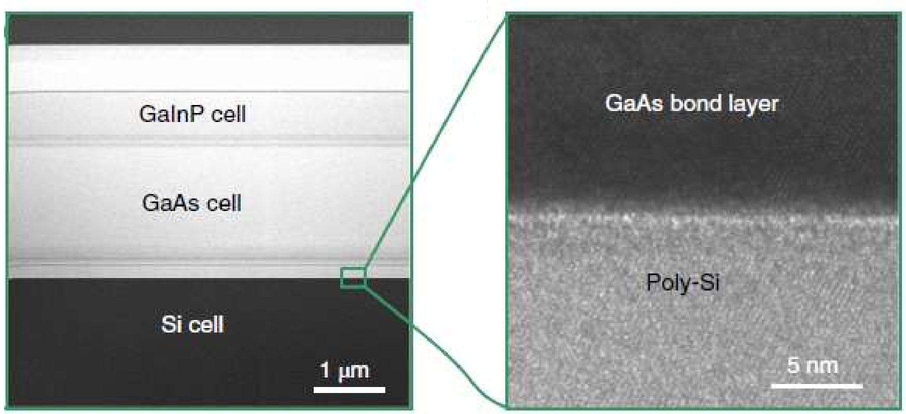
- **Optimal for bonding with III-V cells in tandems**

GaInP/GaAs/Si: 33.3%, wafer bonded, 2-terminal



Inverted growth of III-V layers

Surface-activated (ion beam) wafer bonding on industrial EVG580 ComBond cluster tool. Post-bonding annealing at 290C.

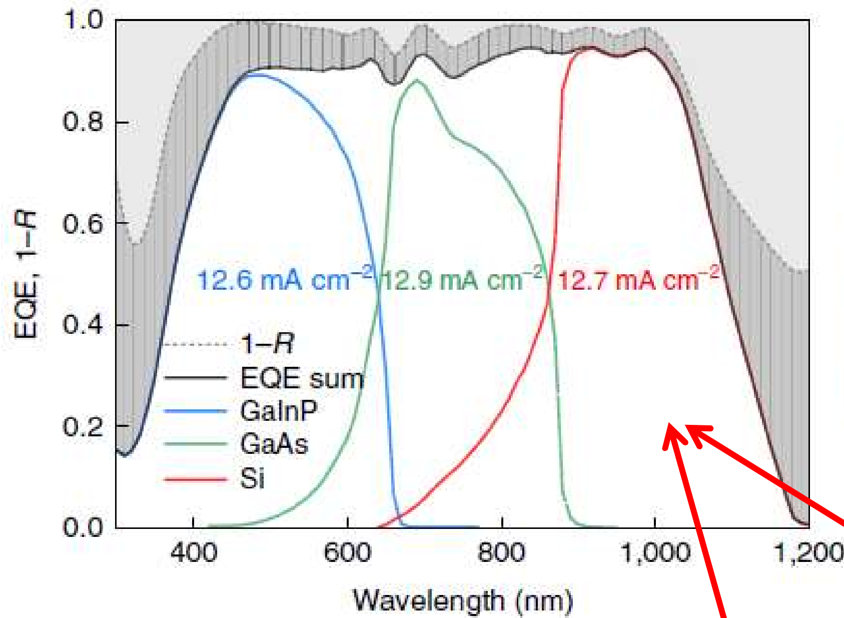


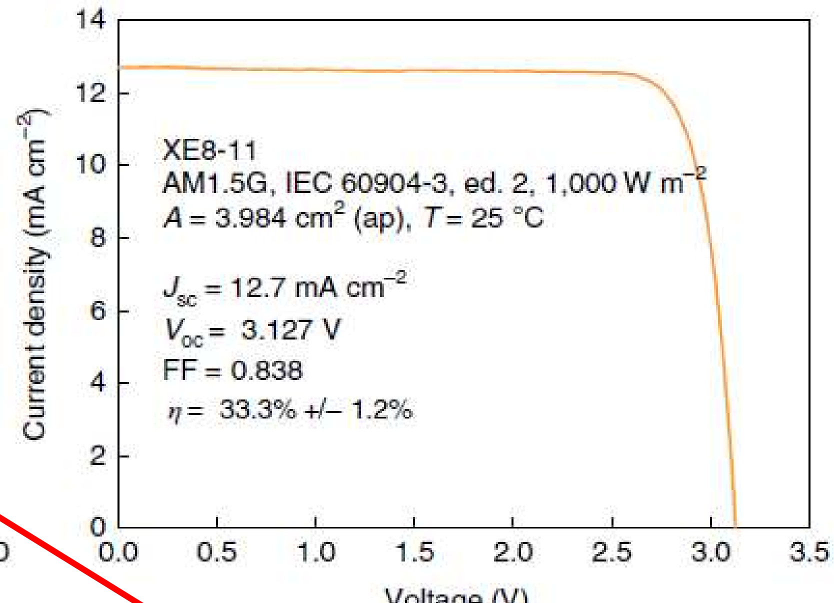
Fraunhofer ISE and partners

https://www.nature.com/articles/s41560-018-0125-0

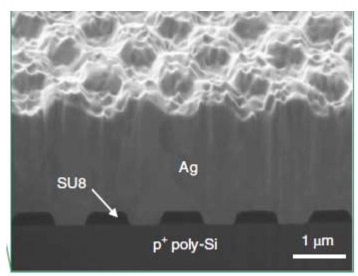
GaInP/GaAs/Si: 33.3%, wafer bonded, 2-terminal

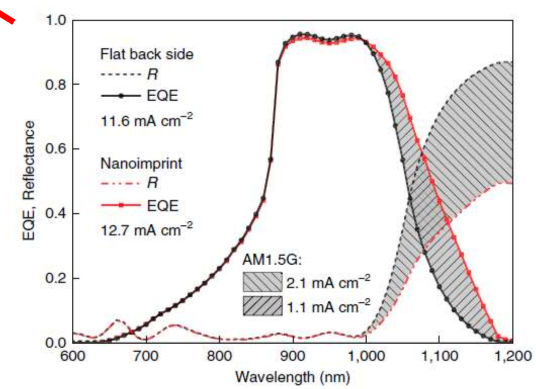
https://www.nature.com/articles/s41560-018-0125-0





nanoimprinted diffraction grating on Si back surface to increase IR EQE:





<u>Contribution to efficiency:</u>

GaInP cell - 14.9%; GaAs cell - 11.1%; Si cell - 7.3%

- **LG's 32.8% GaInP/GaAs + 7.3% Si would give 40.1% (more than any MJ cell)**

Other Si-based tandems

4-terminal III-V mechanical stacks with Si

- All industrially scaled MJ architectures use a 2-terminal design but the advantages of 4-terminal mechanically stacked cells should not be fully ignored.
- Efficient and low-cost micro-inverters may enable multi-terminal cells in the nearest future.
- The most notable result: 35.9% in GaInP/GaAs on Si (NREL, 2017): 30% III-V + 5.9% Si.

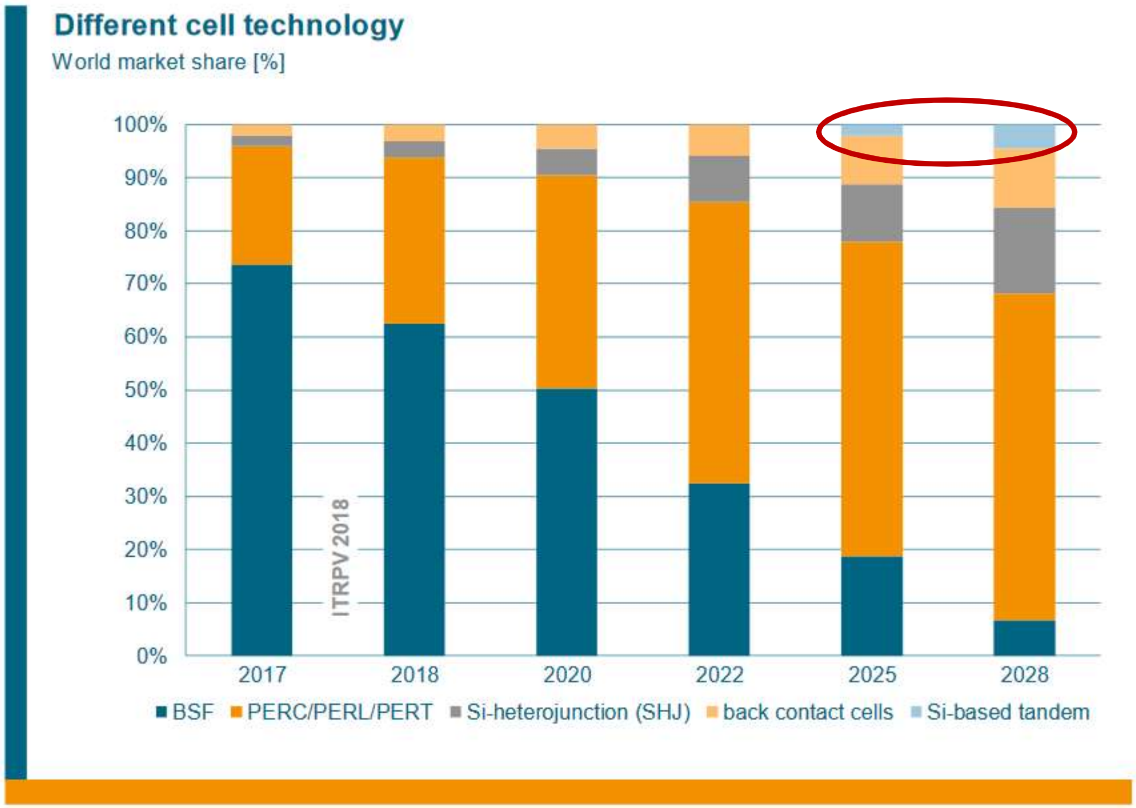
LG's 32.8% GaInP/GaAs + 5.9% Si would give 38.7% (more than Sharp's 3J record and no MM layers required)

- NREL has been working on 3-terminal IBC-Si / III-V tandems with transparent conductive adhesives instead of intermediate contact grids

Two-terminal perovskite-Si tandems

- 27.3% efficiency achieved by Oxford Photovoltaics (2018)

International Technology Roadmap for PV (ITRPV): Si-based

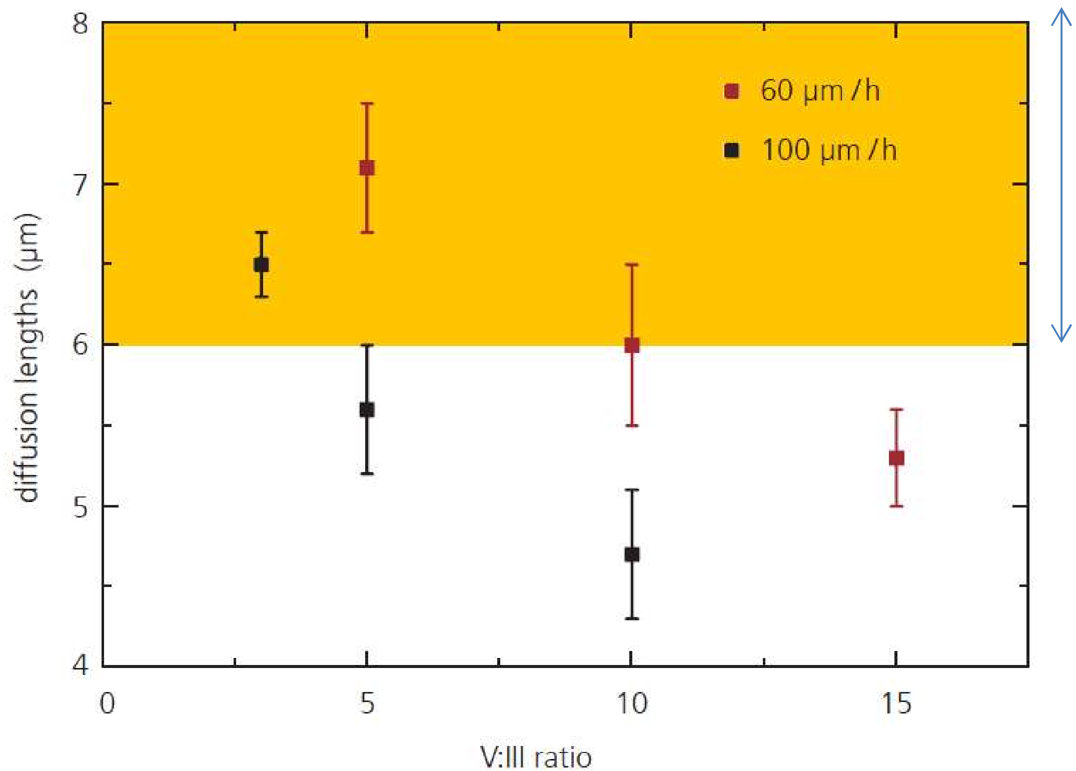


Si-based tandems can be industrialized in the next decade

Source: https://pv.vdma.org/documents/105945/26776337/ITRPV%20Ninth%20Edition%202018%20including%20maturity%20report%2020180904_1536055215523.pdf/a907157c-a241-eec0-310d-fd76f1685b2a

High deposition rates = lower cost

Fraunhofer ISE,
MOVPE
Aixtron AIX2800-G4



Sufficiently high diffusion length

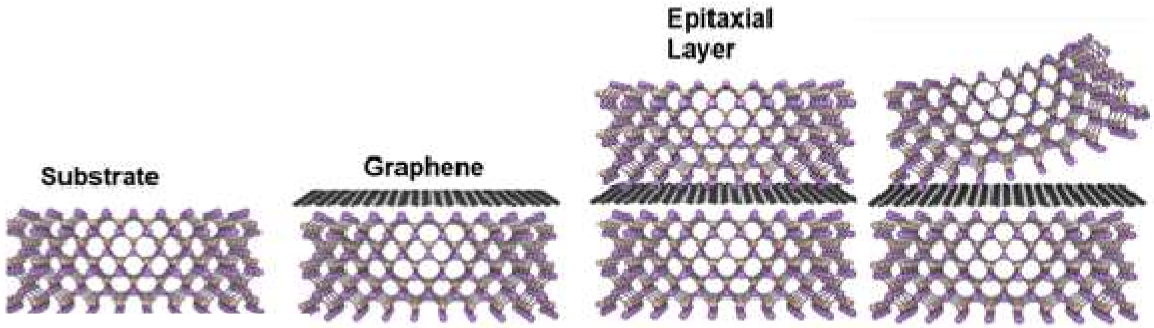
Electron dif. length in p-GaAs as a function of the V/III ratio for deposition rates of 60 µm/h and 100 µm/h

- NREL developed high deposition rate Dynamic Hydride VPE system (no metalorganics)
- 23.7% -efficiency GaInP/GaAs cell was demonstrated with deposition rates of 54 µm/h (GaInP) and 60 µm/h (GaAs). No Al-containing precursors yet: no AlInP window or BSF layers.
- Solution deposition of III-V layers (early stage of research)

Progress with III-V wafers

- Epitaxial liftoff (ELO) allows to reuse expensive GaAs wafers (Alta Devices. LG, Microlink)

- Remote MOCVD epitaxy of GaAs, InP or GaP films through graphene on corresponding substrates and release of III-V films (Prof. J. Kim and his team, MIT)



https://www.nature.com/articles/nature22053

✓ 1 cm^2 GaAs solar cells demonstrated
✓ Good results with flexible electronics/optoelectronics
✓ Obtained $1.5 mil 3-year DOE SETO funding for PV (2018)

- Ternary wafers with variable composition (e.g. InGaAs) instead of binary ones (GaAs, InP) offer additional flexibility in choosing optimal combination of III-V layers in high-efficiency tandems

Conclusions

- Progress with single-junction cell efficiency is steady but slow
- Tandem solar cells, including those with Si sub-cells, is a promising and realistic way to increase solar cell efficiency
- Advances in innovative technologies offer a new potential for more efficient and affordable tandems