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CS INTERNATIONAL CONFERENCE
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Lattice-matched III-V solar cells:

progress and application opportunities

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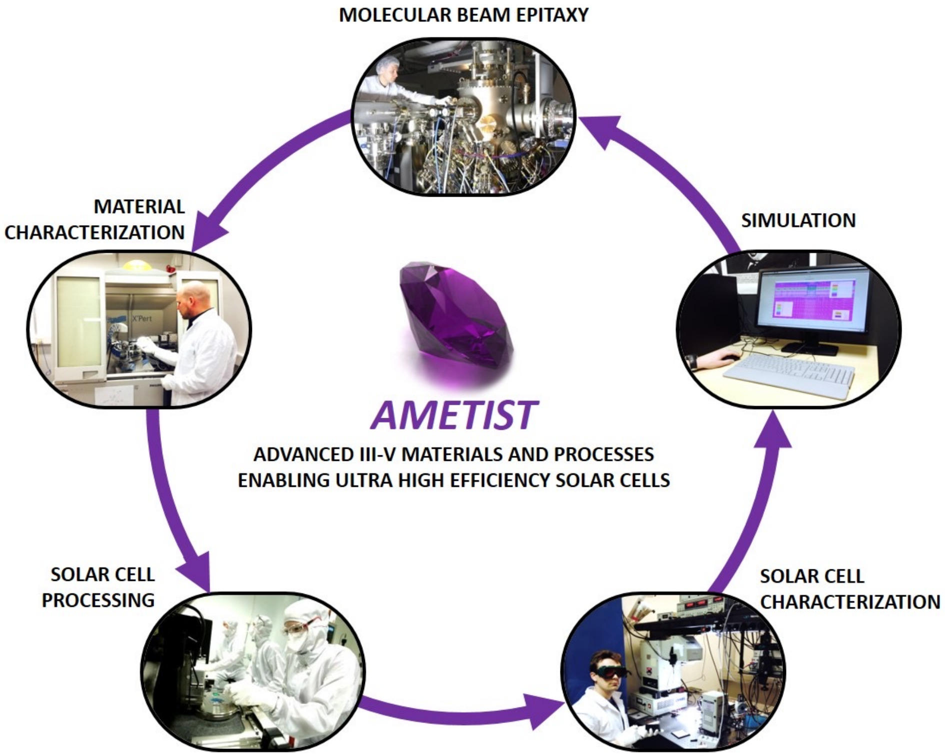
CS International Conference, April 16th-17th 2024, Brussels

Outline

- Motivation
- Epitaxy of lattice-matched GaInNAsSb heterostructures on GaAs
  - State-of-the-art 0.7-0.8 eV junctions
- Progress in developing 4J/5J/6J lattice-matched solar cells
- Forward looking conclusions



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https://projects.tuni.fi/ametist/

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Motivation

Multijunction III–V solar cells

- Key technology for space solar power
- Terrestrial applications in CPV systems

The quest for higher efficiencies

- Reduced weight/power ratio for satellites
- Increased economic feasibility for CPV

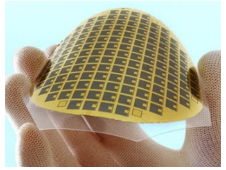
Standard monolithic technology limited to 4J architectures (MOCVD based; requires thick metamorphic buffers)

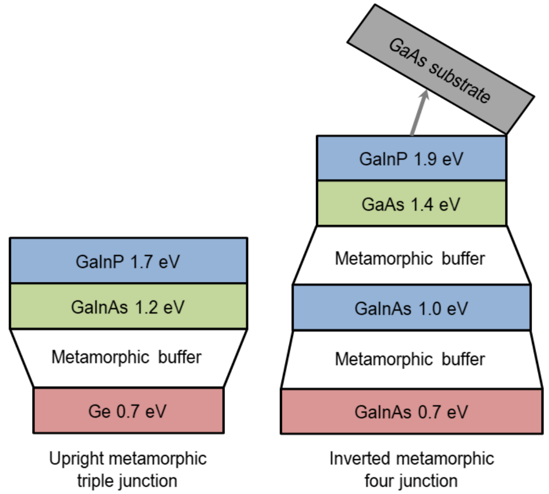
Advanced functionality: thin-film flexible solar cells (proven for lattice-matched architectures)

Flexible solar cells are needed on the ROSA (Roll Out Solar Array) held by the robotic arms at the International Space Station.

CS Mag. Oct. 2021

tf2devices.com





R. France et al,. *MRS Bulletin*, Mar. 2016

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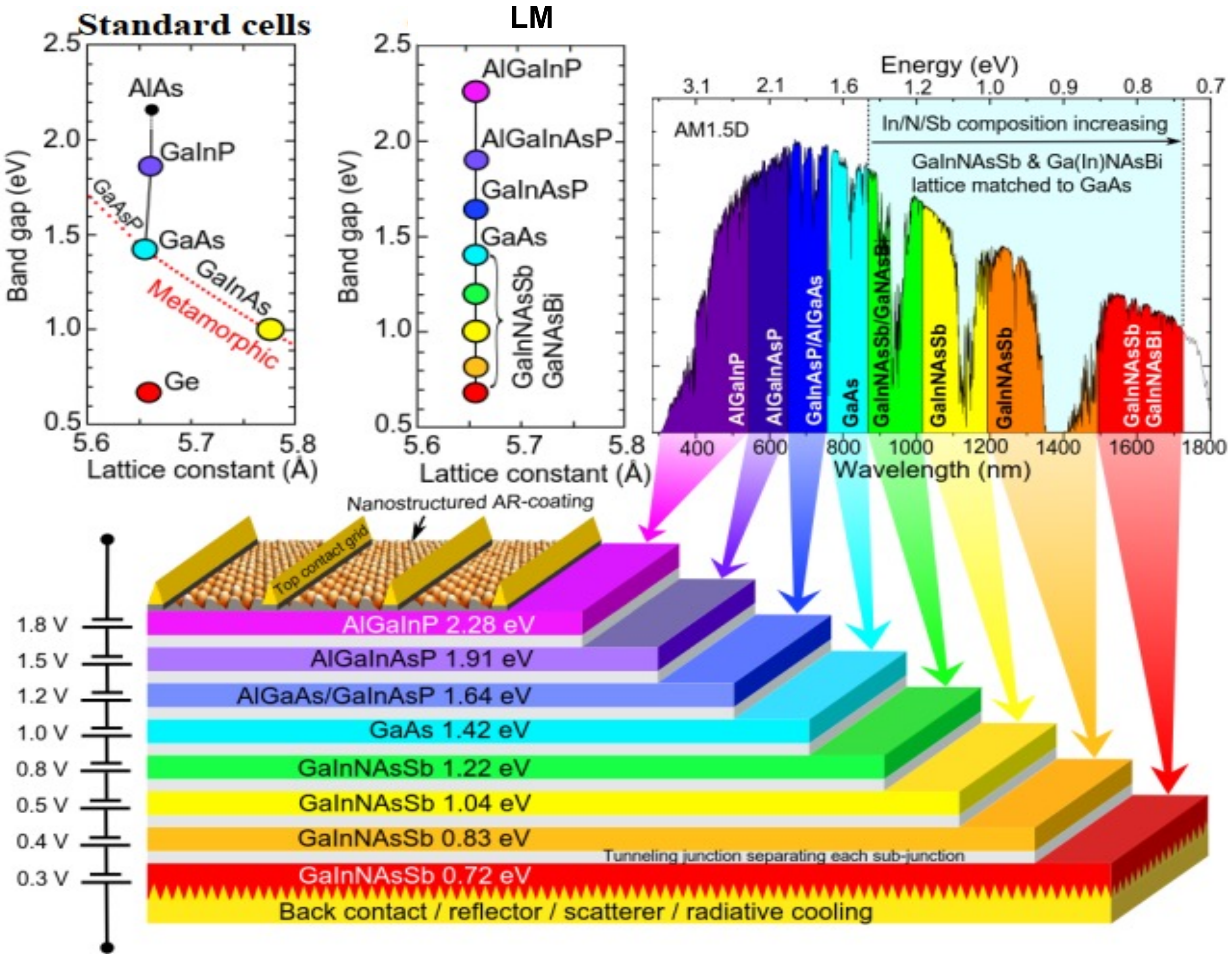
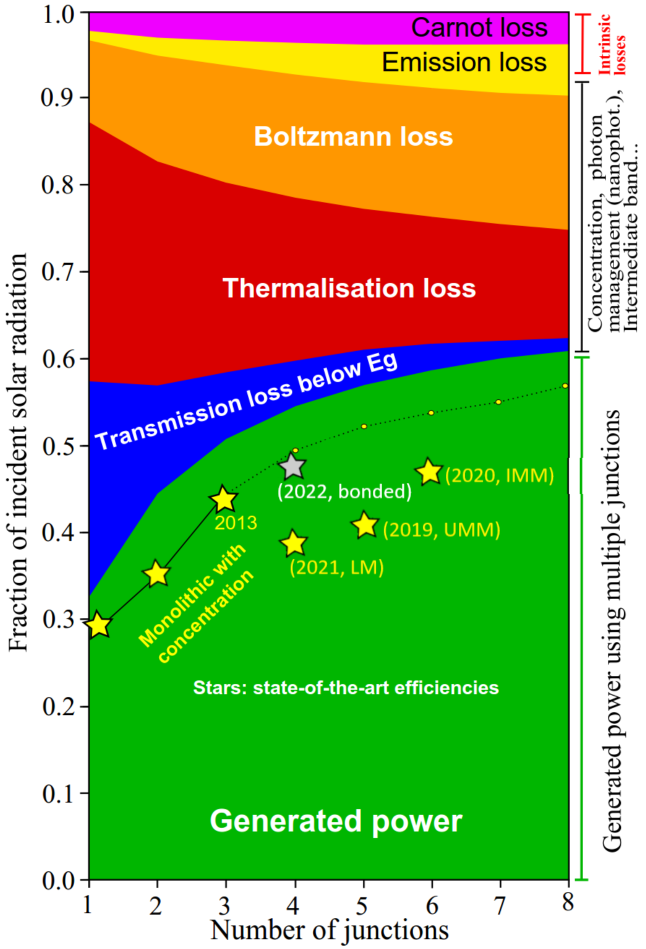
Lattice-matched dilute nitride architecture





Key issues: material quality and current-matching

Adapted from Hirst, Ekins-Daukes: Fundamental losses in solar cells," *Prog. in PV: Res. and App.*, 2011

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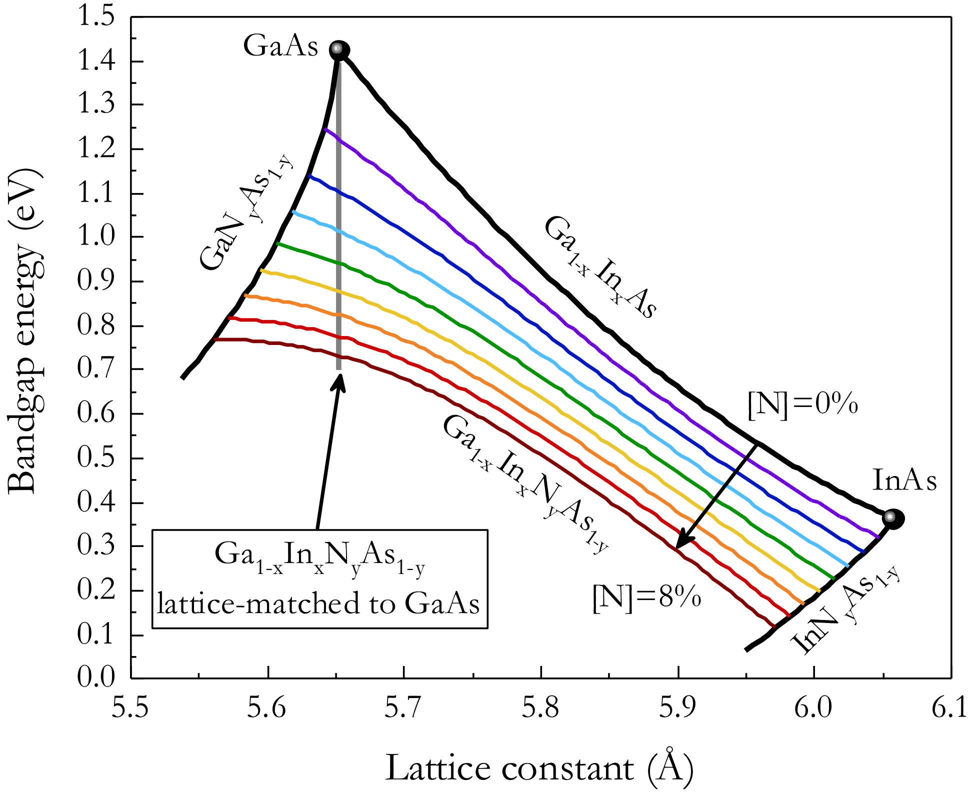
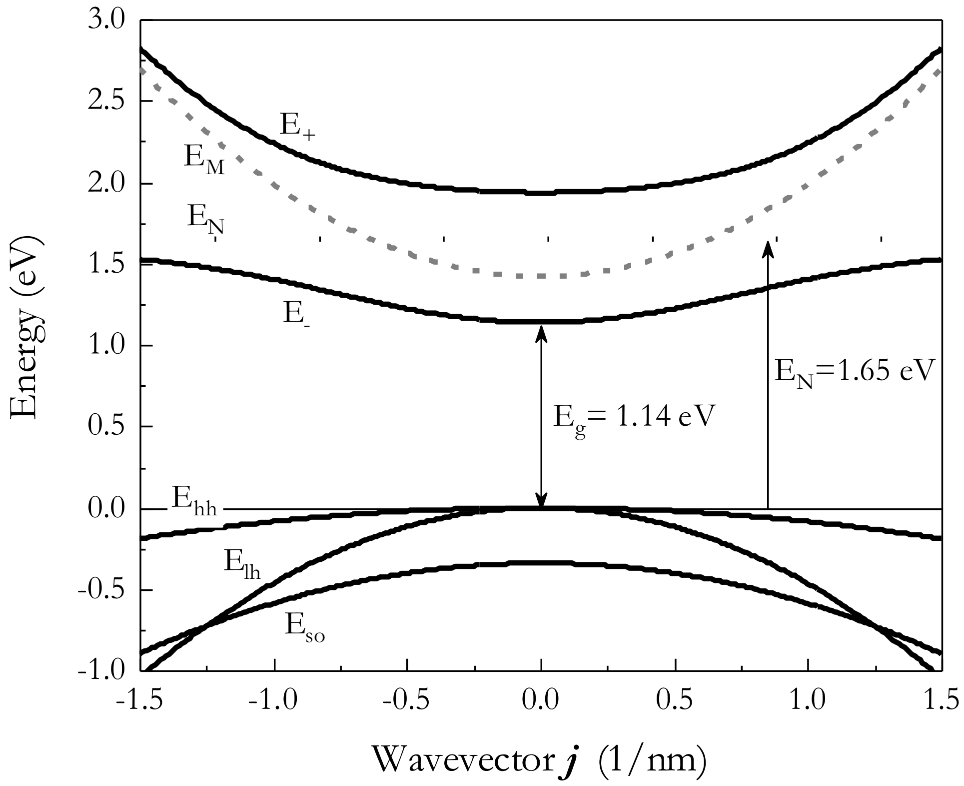
Bandgap engineering with dilute nitrides

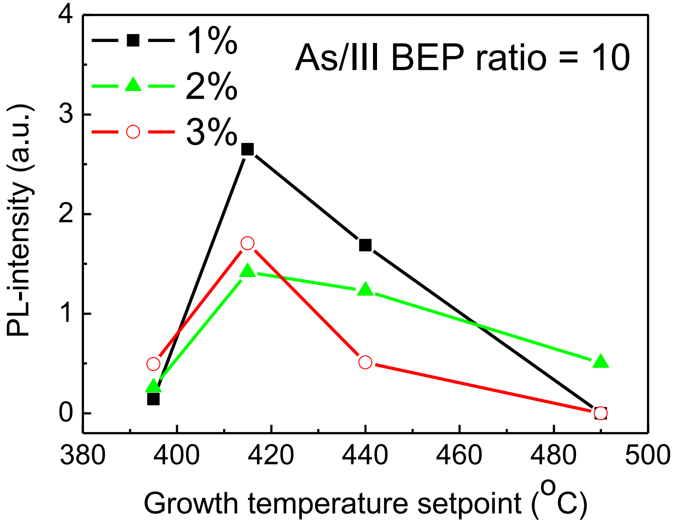


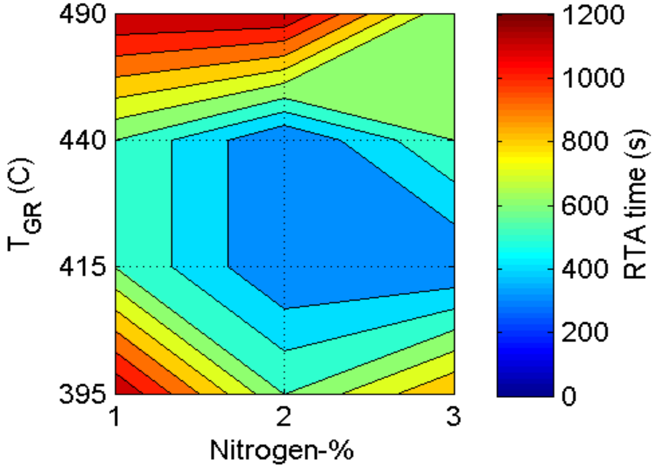


Electronic band structure for $GaN_{0.02}As_{0.98}$ (BAC)

Reaching 0.7-0.8 eV on GaAs requires 6-8% of nitrogen

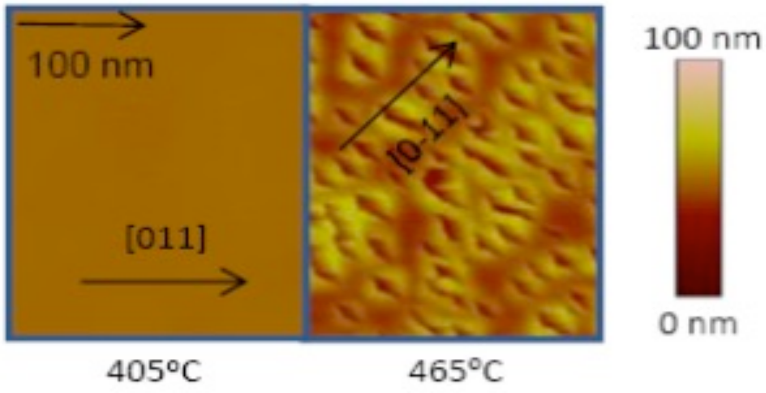
MBE growth of 1 eV GaInNAsSb junctions



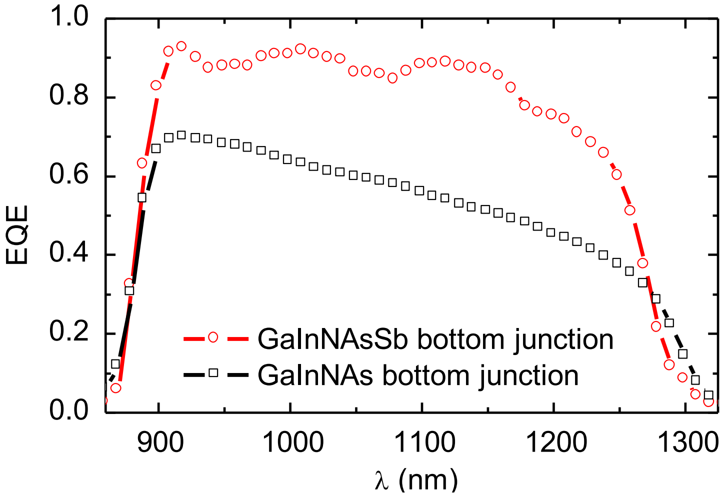


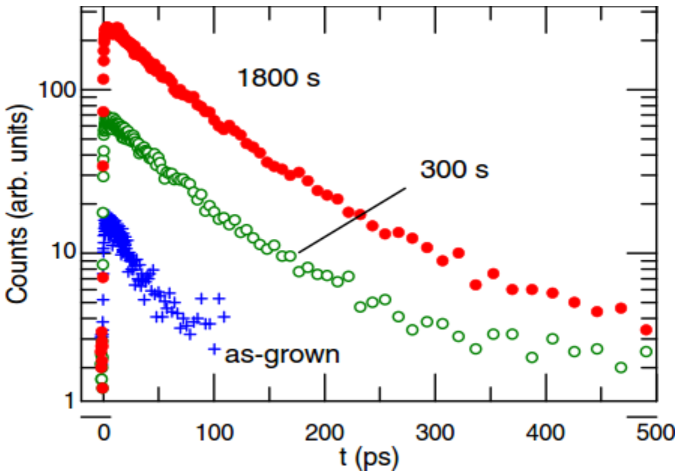
Parameter	Value
Doping type	p
Doping level	< $1x10^{16}$ cm^{-3}
Electron mobility	350-400 cm^2/Vs
Hole Mobility	80-100 cm^2/Vs
Carrier lifetime	> 0.5 ns

Requirements for GaInNAsSb junctions



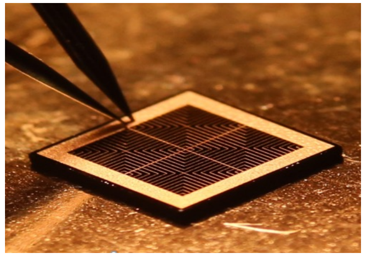
Aho et al., SOLMAT ***124,*** *150 (2014)*

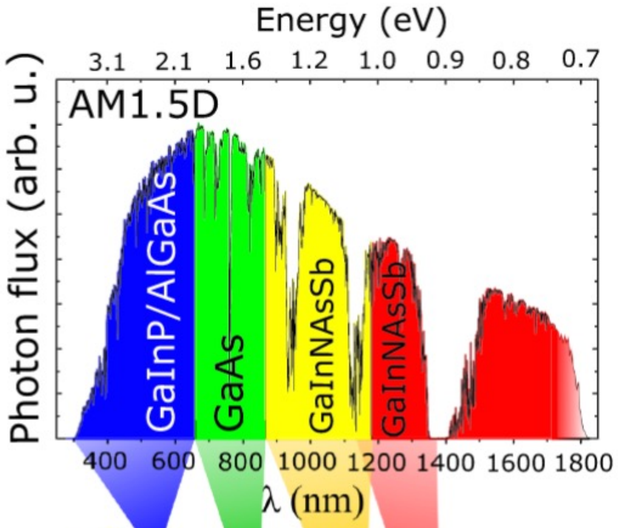


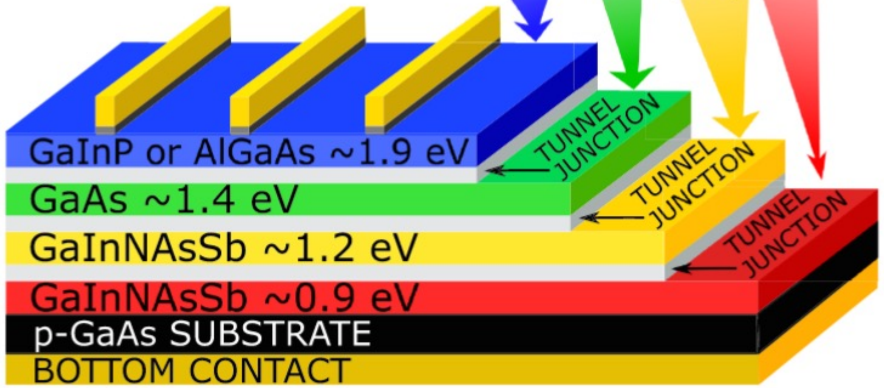


Polojärvi et al., Appl. Phys. Lett. **108**, 122104 (2016)

4J cells with two GaInNAsSb junctions

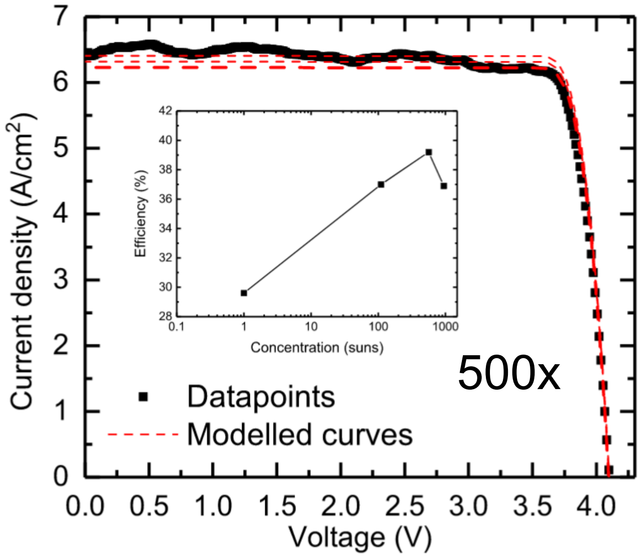


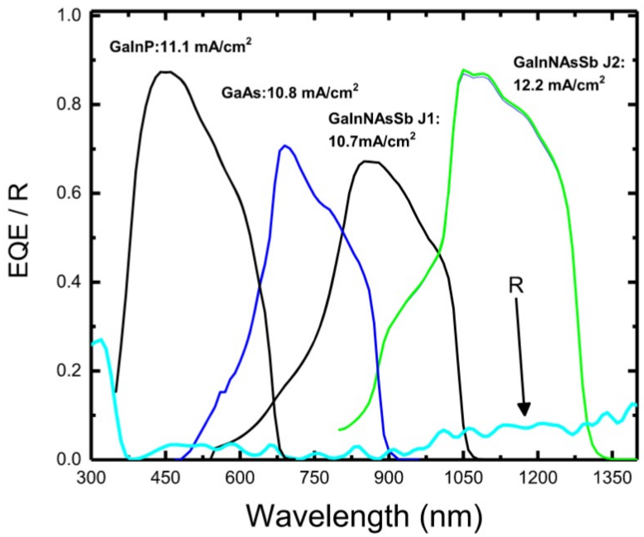




4J with two dilute nitride bottom junctions

Aho *et al.*, Prog Photovolt Res Appl. 29: 869– 875 (2021)





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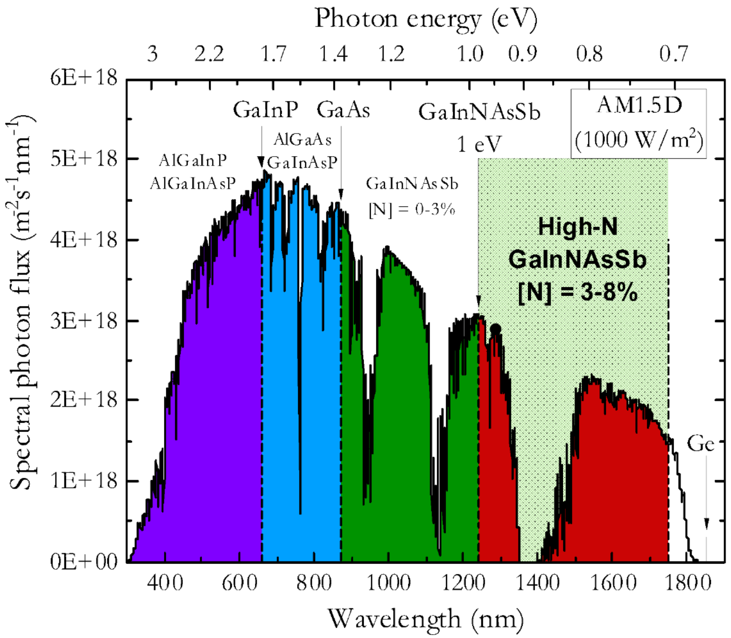
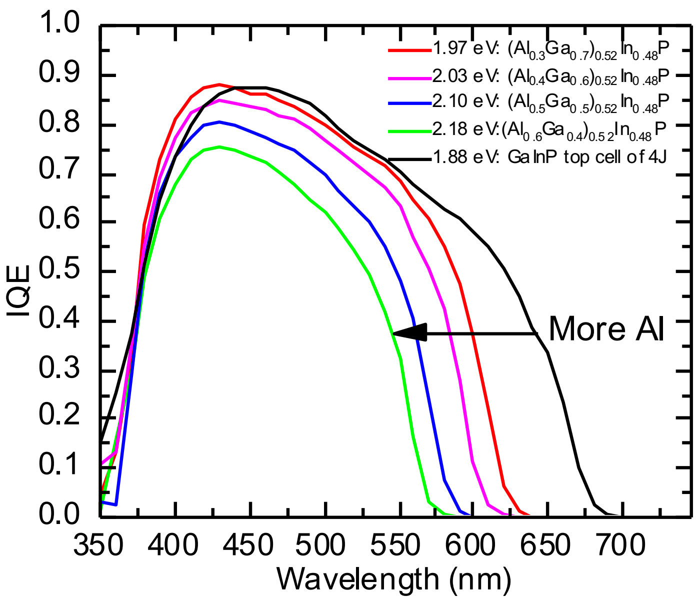
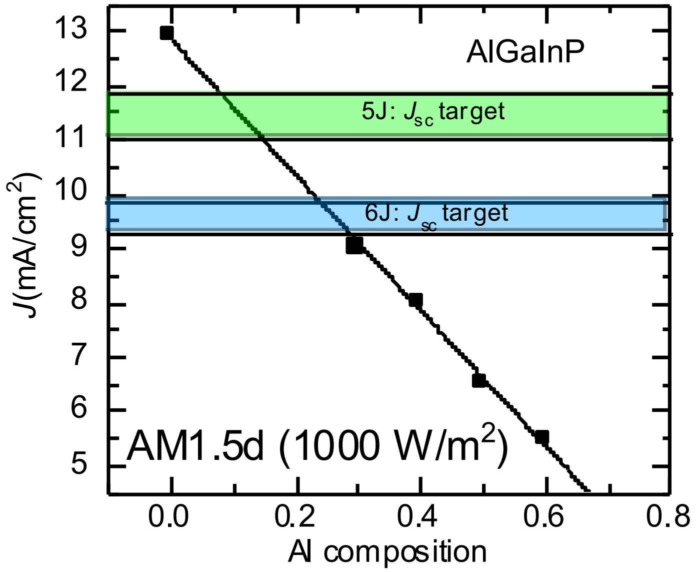
Lattice-matched designs with 5+ junctions

- **Extension to long wavelength using GaInNAsSb junctions with E_g<0.9 eV ([N] >5%)**
- **Current matching also requires development of AlGaInP top junction (>2 eV)**







Epitaxy optimization of 0.8 eV GaInNAsSb

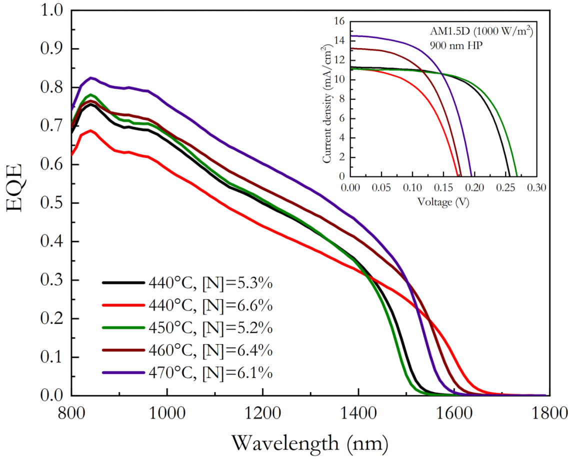
- **Lattice-matched high-N p-i-n junctions grown on 4” p-GaAs**
- **E_g target~0.8 eV (N ~5-6%; In ~ 15%; Sb ~2-3%)**
- **Change of growth parameters:** T_g, As/III BEP ratio, Sb flux
- All samples *in*-situ annealed

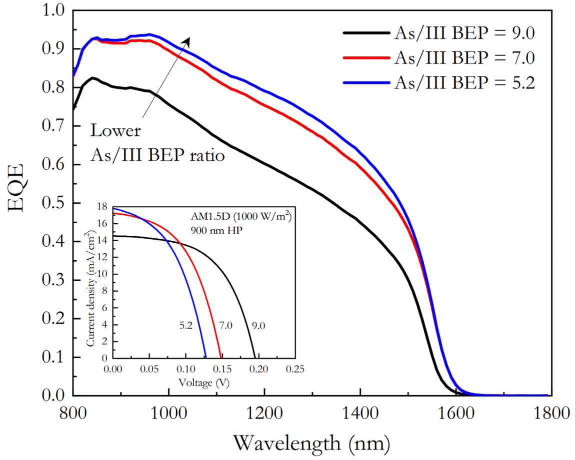
	Sample	$[In]_{nominal}$ (%)	$[N]_{nominal}$ (%)	T_g (°C)	As/III BEP ratio	Sb BEP (Torr)
	A	15	5.2	440	9.0	1.0×10^{-8}
	B	15	5.7	440	9.0	1.0×10^{-8}
T_g	C	15	5.2	450	9.0	1.0×10^{-8}
	D	15	5.2	460	9.0	1.0×10^{-8}
	E	15	5.0	470	9.0	1.0×10^{-8}
	F	15	5.0	480	9.0	1.0×10^{-8}
As	G	15	5.0	470	7.0	1.0×10^{-8}
	H	15	4.9	470	5.2	1.0×10^{-8}
Sb	I	15	4.8	470	7.0	1.4×10^{-8}
	J	14	4.8	470	7.0	1.8×10^{-8}
	K	14	4.8	480	7.0	1.8×10^{-8}

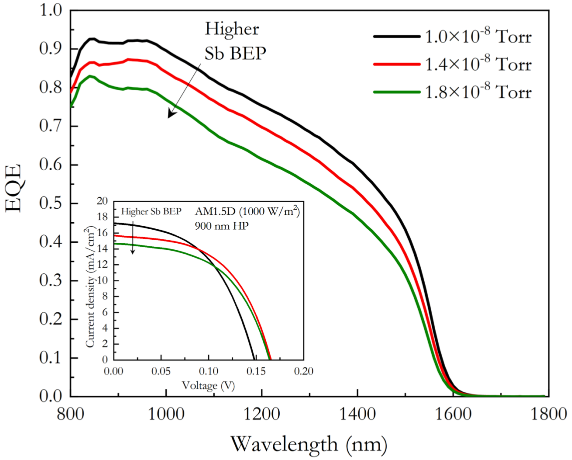
Layer	Thickness	Doping	Function
n-GaAs	300 nm	1×10^{19} cm^{-3}	Contact layer
n-$Al_{0.35}Ga_{0.65}As$	40 nm	2×10^{18} cm^{-3}	Window
n-GaAs	100 nm	1×10^{18} cm^{-3}	Emitter
i-GaInNAsSb	1.2 µm		Absorber
p-GaAs	100 nm	5×10^{18} cm^{-3}	Base
p-$Al_{0.35}Ga_{0.65}As$	100 nm	5×10^{18} cm^{-3}	BSF
p-GaAs	300 nm	5×10^{18} cm^{-3}	Buffer
p-GaAs substrate (625 µm)			

Isoaho *et al.*, Sol. Energy Mater. Sol. Cells (2022)

Effects of growth parameters







T_g ↑:

- Enhanced N incorporation at ≥ 460 °C
  - More recombination with higher N
  - Carrier lifetimes 4-5 ns → < 1 ns
  - Reduction of V_{oc}
- Phase separation at 480°C
  - Suppressed with more Sb
- p-type background doping ↓
  - 10^{17} cm^{-3}→ 10^{16} cm^{-3}
  - EQE and J_{sc} ↑

As ↓:

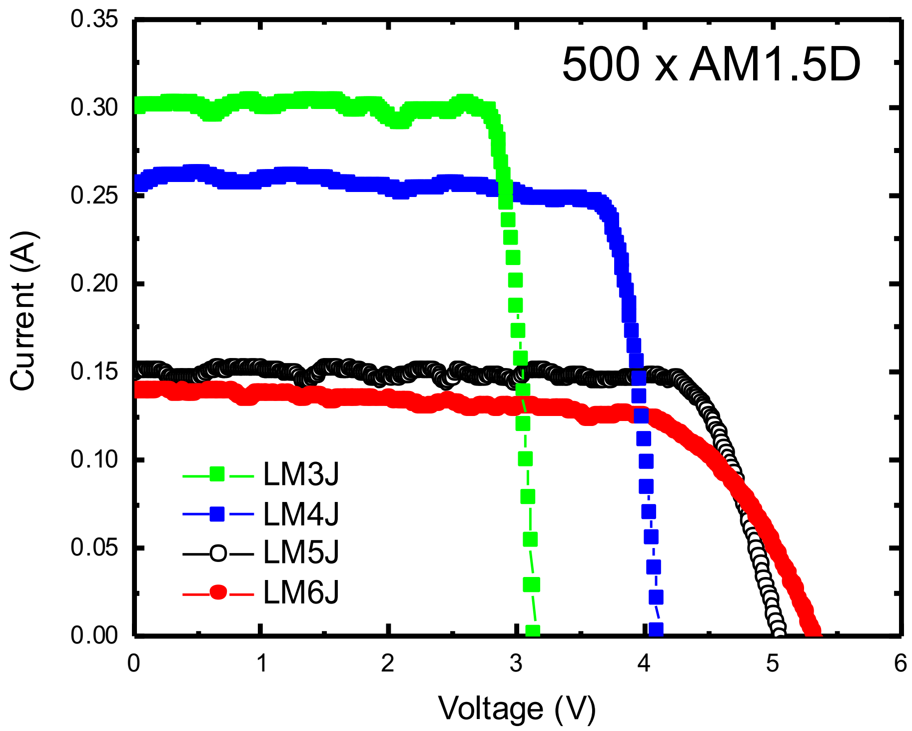
- Enhanced N and Sb incorporation
  - More recombination with higher N
  - Carrier lifetimes 1.5 ns → 0.5 ns
  - Reduction for V_{oc}
- p-type background doping ↓
  - $2 \cdot 10^{16}$ cm^{-3}→ $2 \cdot 10^{15}$ cm^{-3}
  - EQE and J_{sc} ↑
  - >90% EQE values achieved

Sb ↑:

- Slight reduction in recombination
  - Carrier lifetimes 0.6 ns → 0.7 ns
  - +20 mV for V_{oc}
- p-type background doping ↑
  - $2 \cdot 10^{15}$ cm^{-3}→ $7 \cdot 10^{15}$ cm^{-3}
  - EQE and J_{sc} ↓
- Combined effect → +10% in output power with intermediate Sb

Isoaho *et al.*, Sol. Energy Mater. Sol. Cells (2022)

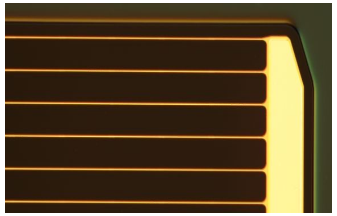
LM MJSCs: From 3 to 6 junctions



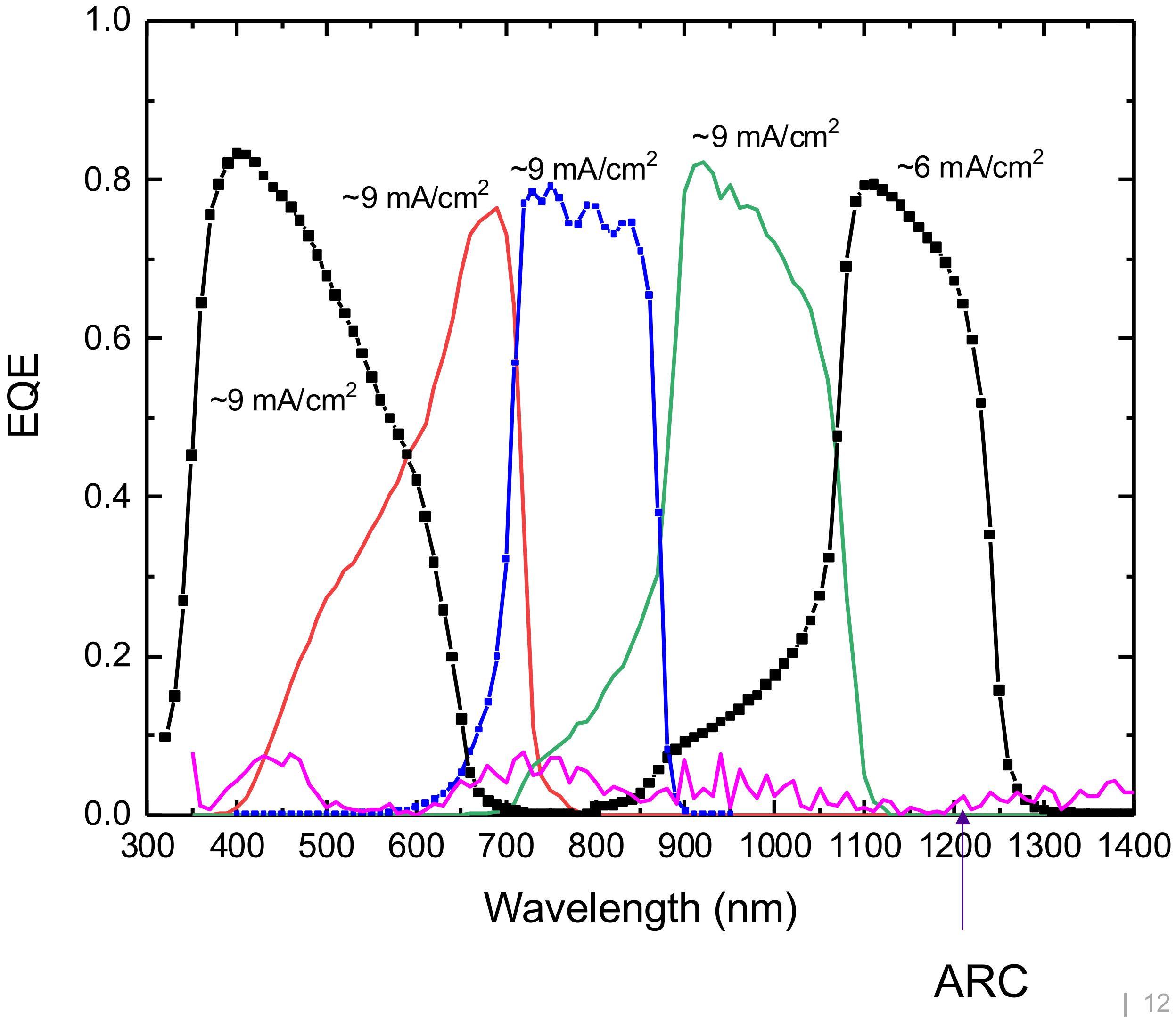
Measured LIV characteristics for lattice-matched solar cells under 500 x AM1.5D illumination.

LMSC	$J_{sc\text{-}meas}/J_{sc\text{-}target}$ (mA/cm^2)	V_{oc} (V)	Eg (eV)
3J	13/14	3.1	1.9/1.4/1.0
4J	11/12	4.1	1.9/1.4/1.2/0.9
5J	6/9	5.1	1.9/1.7/1.4/1.1/0.9
6J	6/8	5.3	1.9/1.7/1.4/1.2/1.1/0.8

5J:GaInP/AlGaAs/GaAs/GaInNAsSb/GaInNAsSb

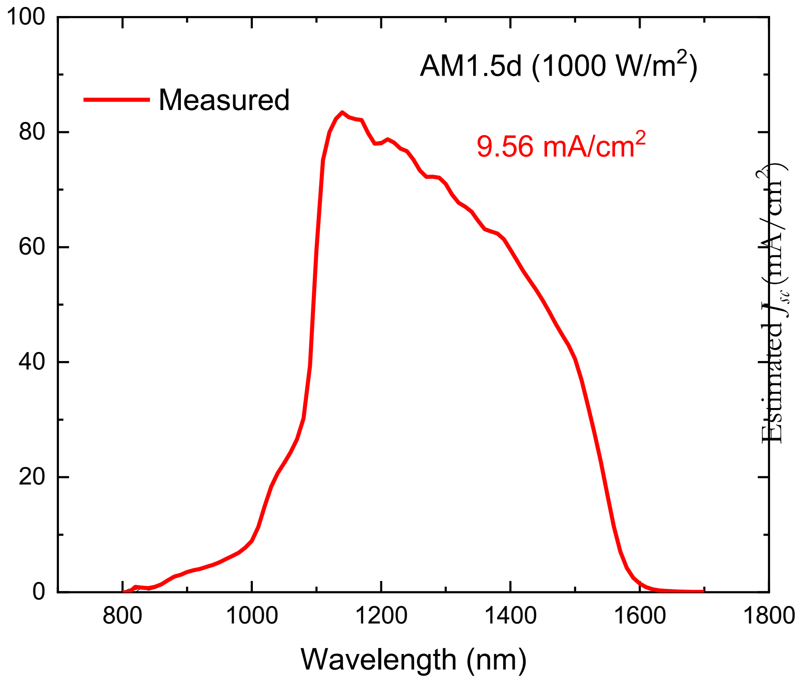


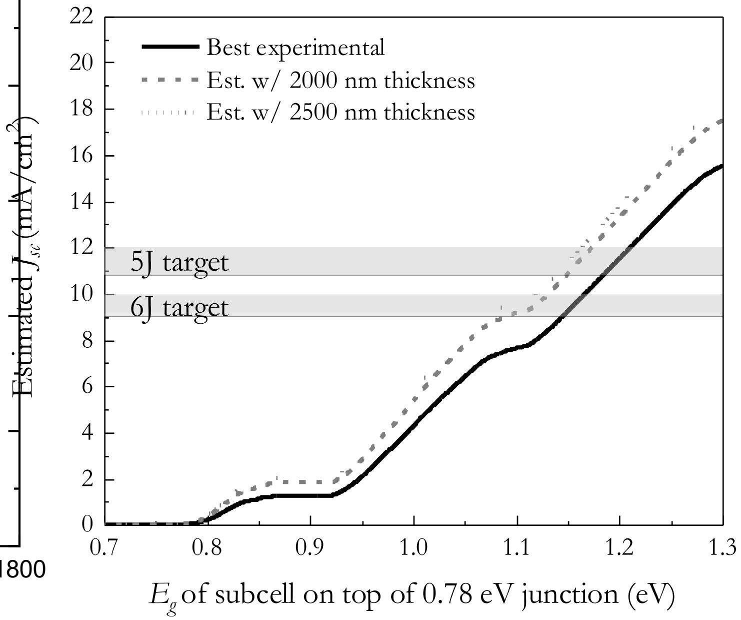
- 6 layers ARC coating
- Good voltage per junction
  W_{oc} (500x) = 0.39 V (similar to LM3J)
- Small cell area of 0.04 cm^2
- EQE: Bottom SC limits the Jsc
  - Too large E_g (6 mA/cm^2 vs. 9 mA/cm^2)



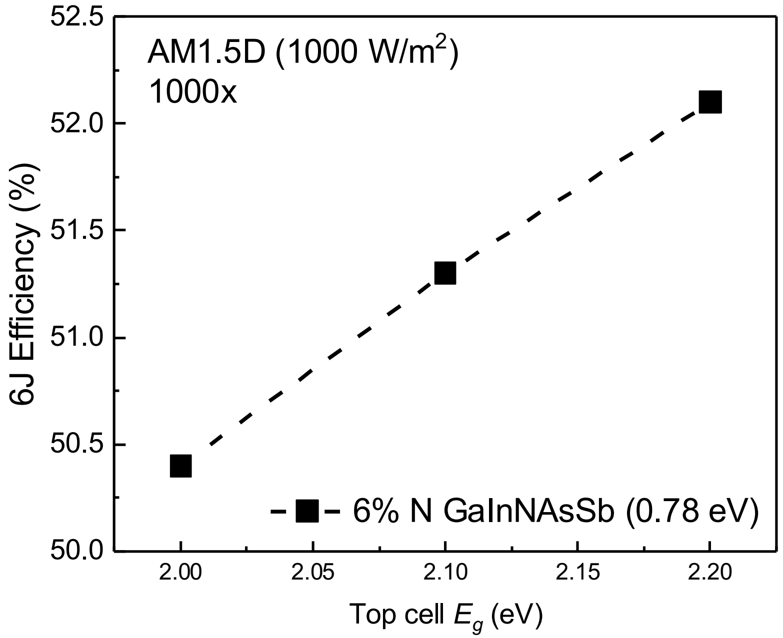
Prospects for 6J integration

- Current-matching for ~0.8 eV sub-cells is achievable
- Concentrated efficiencies exceeding 50% are realistic with 6J employing the best experimental 0.78 eV GaInNAsSb junctions (top junction require larger bandwidth)



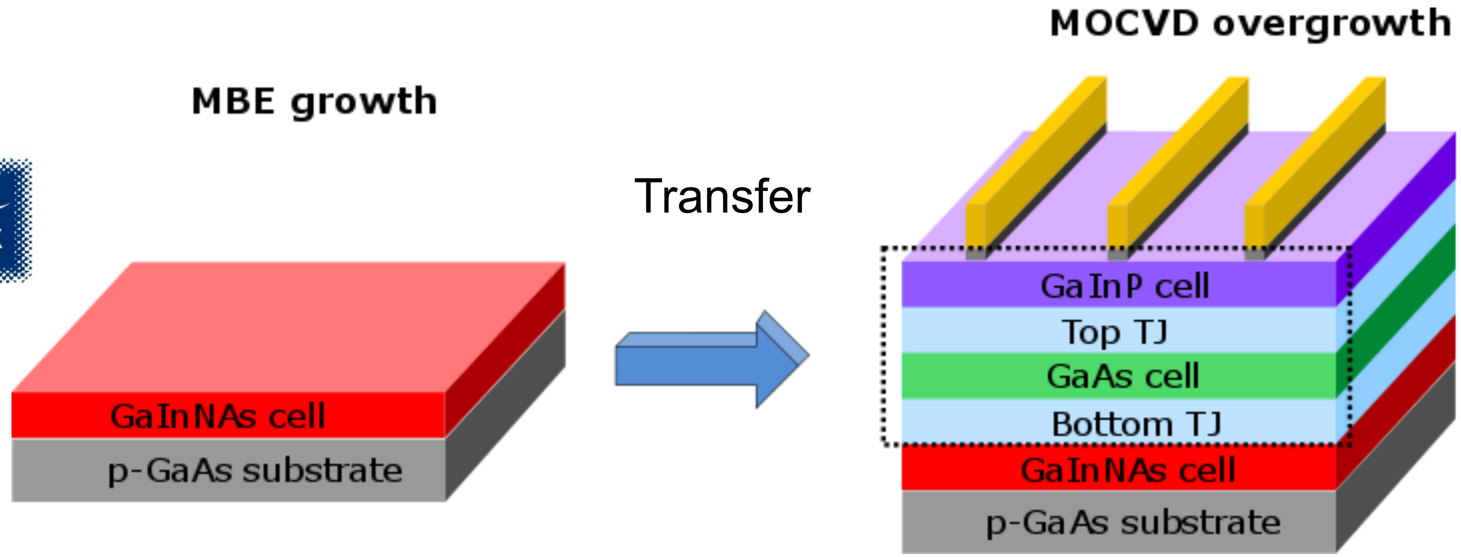


Isoaho *et al.*, Sol. Energy Mater. Sol. Cells (2022)



Isoaho *et al.*, Sol. Energy Mater. Sol. Cells (2019)

Technology compatible with MOCVD



ORC, Tampere (VEECO GEN20 MBE) **CESI, MILAN (VEECO 450 MOCVD)**

Growth on 100 mm GaAs (100) substrate

Combines the technological and economic advantages of both the MBE and MOCVD processes to produce MJ solar cells at reduced cost and higher throughput with respect to MBE process.

Key issues: transfer process; nucleation layers; MOCVD thermal budget

A. Tukiainen at al., **High-efficiency GaInP/GaAs/GaInNAs solar cells grown by combined MBE-MOCVD technique;** 2016

Progress in PHOTOVOLTAICS

MBE/MOCVD on Ge substrate

+

Public report ESA Project “Impro33”

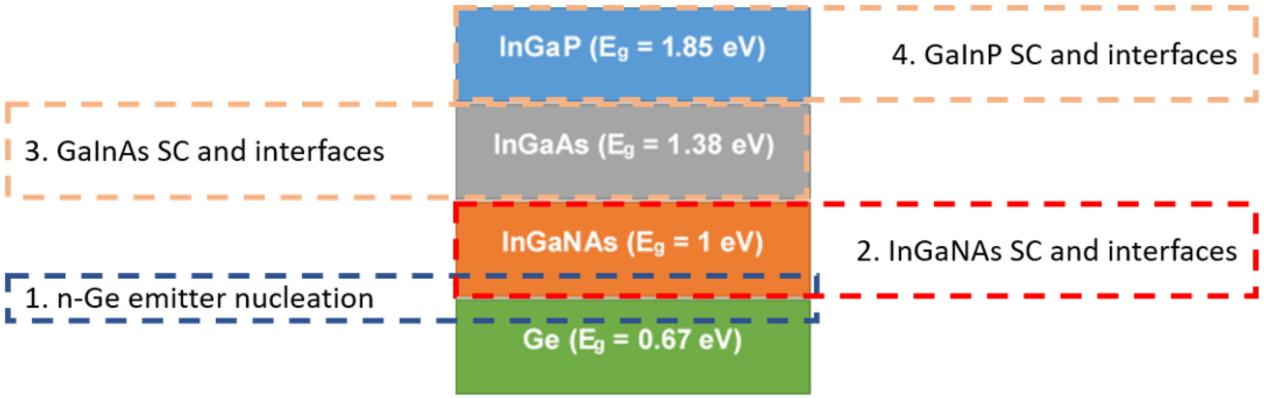
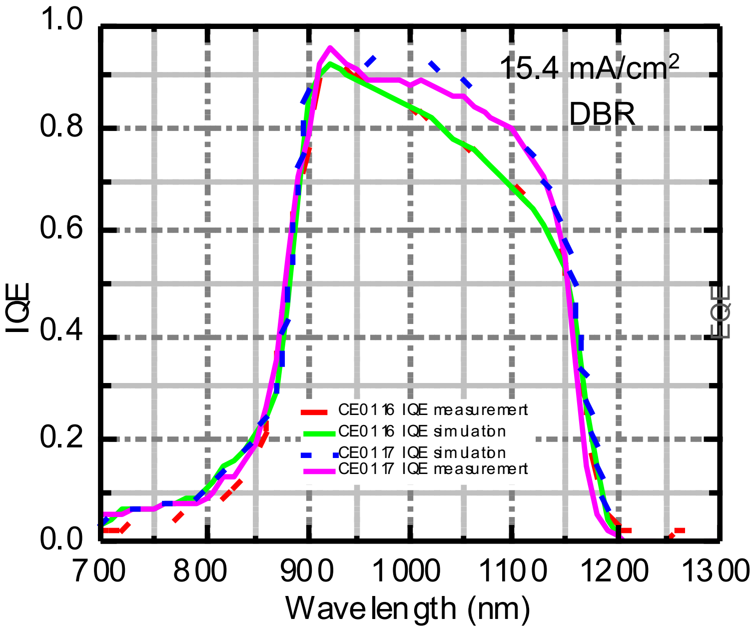
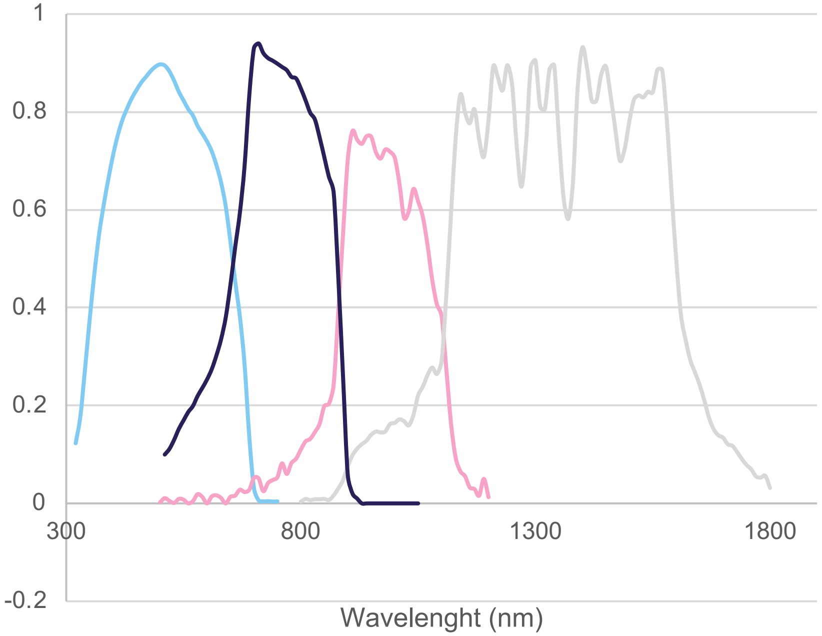


Fig. 2: Basic principle of the combined MBE-MOCVD technique.





Forward looking conclusions

- MBE technology for dilute-nitride solar cells is mature enough for architectures with more than 4 junctions. Suitable for mass production.
- High quality low-bandgap GaInNAsSb materials (N ~ 6%) demonstrated.
- The highest bandgap junction needs to be developed as well as several processing aspects (e.g., grid design, passivation, ARC, mounting etc.)
- The 50% efficiency target under CPV conditions is feasible.
- Lattice-matched solar cell technology is particularly attractive for implementing thin-film architectures for specialized applications.

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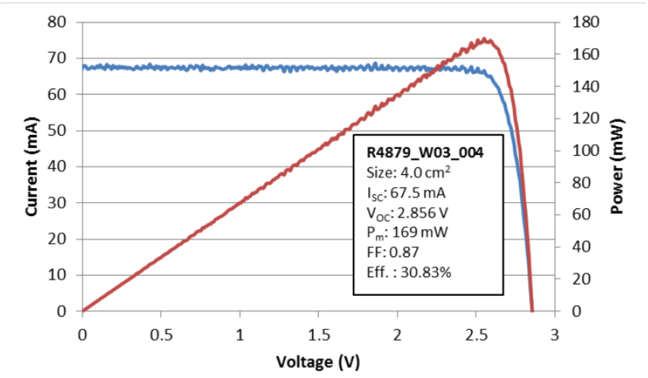
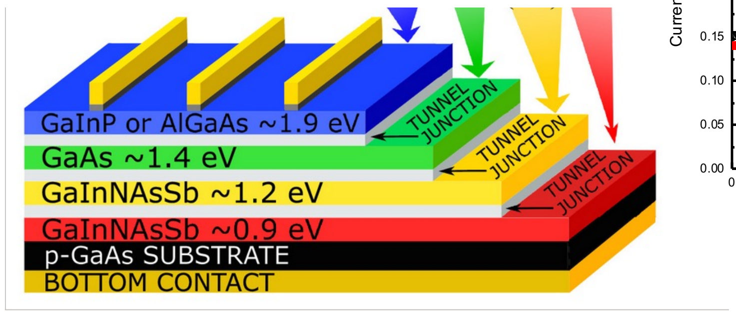
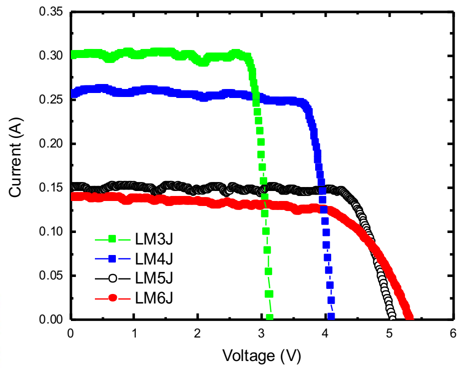
From materials to applications







WINSE POWER

2023: Light-based ENERGY solutions winsepower.com

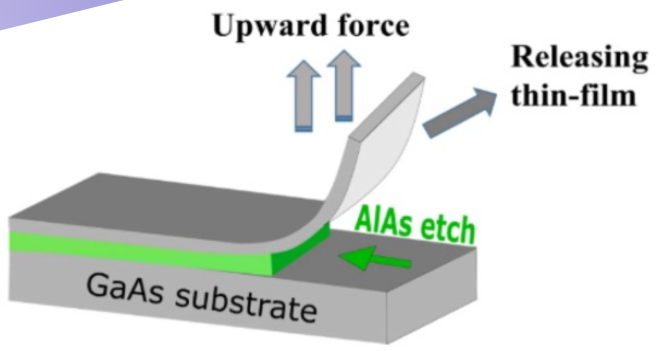
2022 ~0.8 eV GaInNAsSb and 5-6 J prototypes

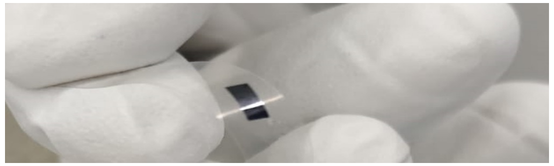
2020: MBE CPV LM4J@ 500X

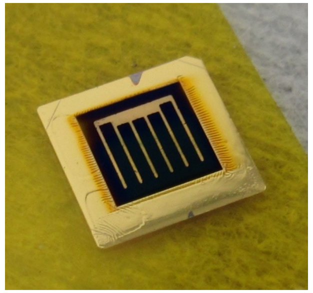
2016: ~31% MBE-MOCVD Space 3J

Materials development projects on GaAs and Ge

Prabudeva et al., "***Epitaxial lift-off process for GaAs solar cells controlled by InGaAs internal sacrificial stressor layers and a PMMA surface stressor***", SolMat 248 (2022)







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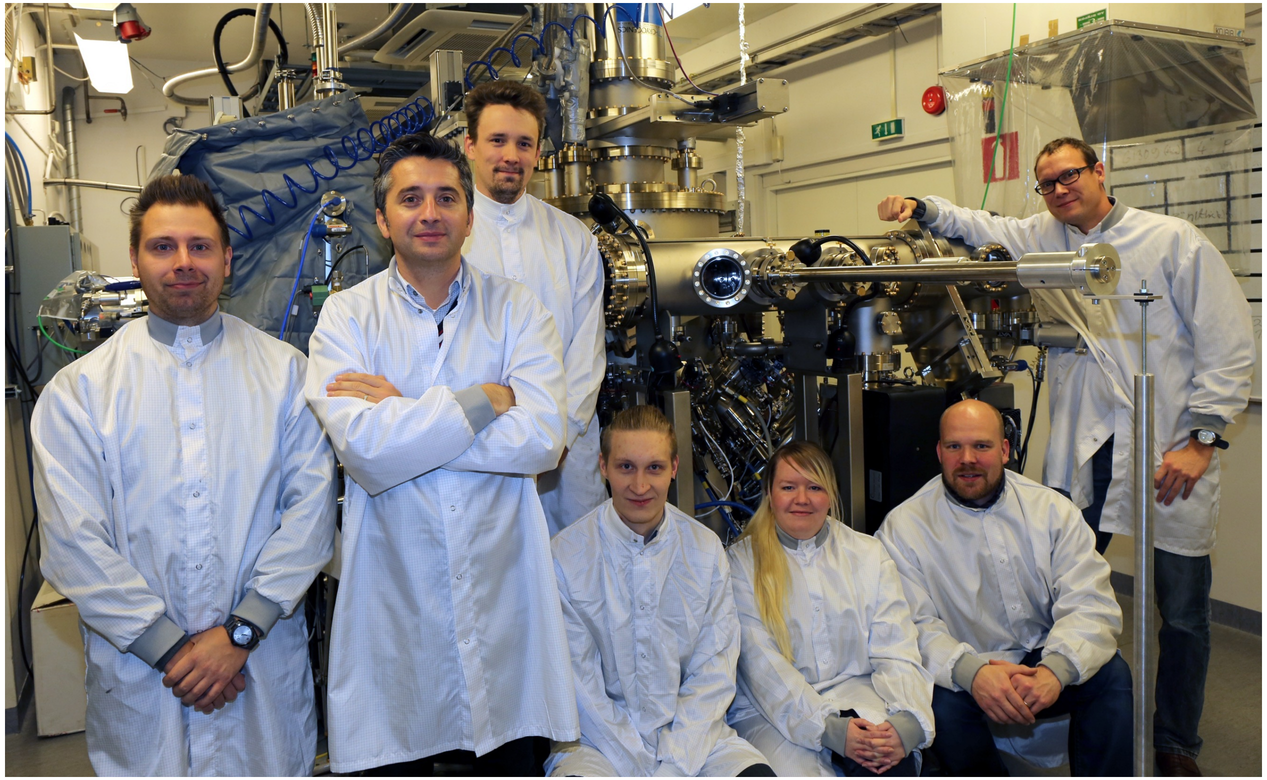
Thank you!

Dr. Antti Tukiainen, Dr. Arto Aho, Dr. Ville Polojärvi
Dr. Timo Aho, Dr. Riku Isoaho, Dr. Jarno Reuna, Marianna Vuorinen, Prabudeva Ramu, Veikka Nikander, Elina Anttola, Antti Fihlman



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Financial support:
ERC AdG project AMETIST
(ERC-2015-AdG 695116)