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ESA Contract No. 4000128123/19/NL/FE

(AO/1-9816/19/NL/FE)

“Impro33“ – Improved multi-junction solar cells with up to 33% efficiency at end of life

Final Presentation – 13th October 2022

(held via WebEx)

Agenda

➢ 9:30	Welcome + Project Overview	AZUR	~ 15 min.
➢ 9:45	Results on TBB's @AZUR	AZUR	~ 15 min.
➢ 10:00	Results on TBB's @ISE	ISE	~ 15 min.
➢ 10:15	Results on TBB's @TF2	TF2	~ 10 min.
➢ 10:25	Results on TBB's @CESI	CESI	~ 10 min.
➢ 10:35	Results on InGaNAs@TAU	TAU	~ 25 min.
➢ 11:00	Results on inno. Ge wafers	AZUR	~ 10 min.
➢ 11:10	Summary & Conclusions	AZUR	~ 5 min.
➢ 11:15	Discussion / Questions	ALL / ESA	~ 45 min.
➢ 12:00	End of Meeting		

Content

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- Objectives
- Project overview (WBS & Gantt)
- Results on investigated ‚Technoogy Building Blocks‘:

- AZUR:	UMM cell technology, thin & flex. cells & SCA‘s
- ISE & TF2:	IMM cell technology
- CESI & TAU:	InGaNAs cell technology
- Umicore:	innovative Ge substrates

- Summary and Conclusions

Main objectives (targets & reqirements)

Four primary objectives:

- Increase EOL eff.	Req.: >26%	✓	Target: 33%	✗
- Increase BOL eff.:	Req.: >30%	✓	Target: 35%	✗
- Reduction of weight:	Req.: <50 mg/cm²	✓	Target: <20 mg/cm²	✓
- mech. flexibile SCAs:	Req./Target.:	n.d.	R_{bend} = 50 mm	(✓)

Project overview – WBS and work share

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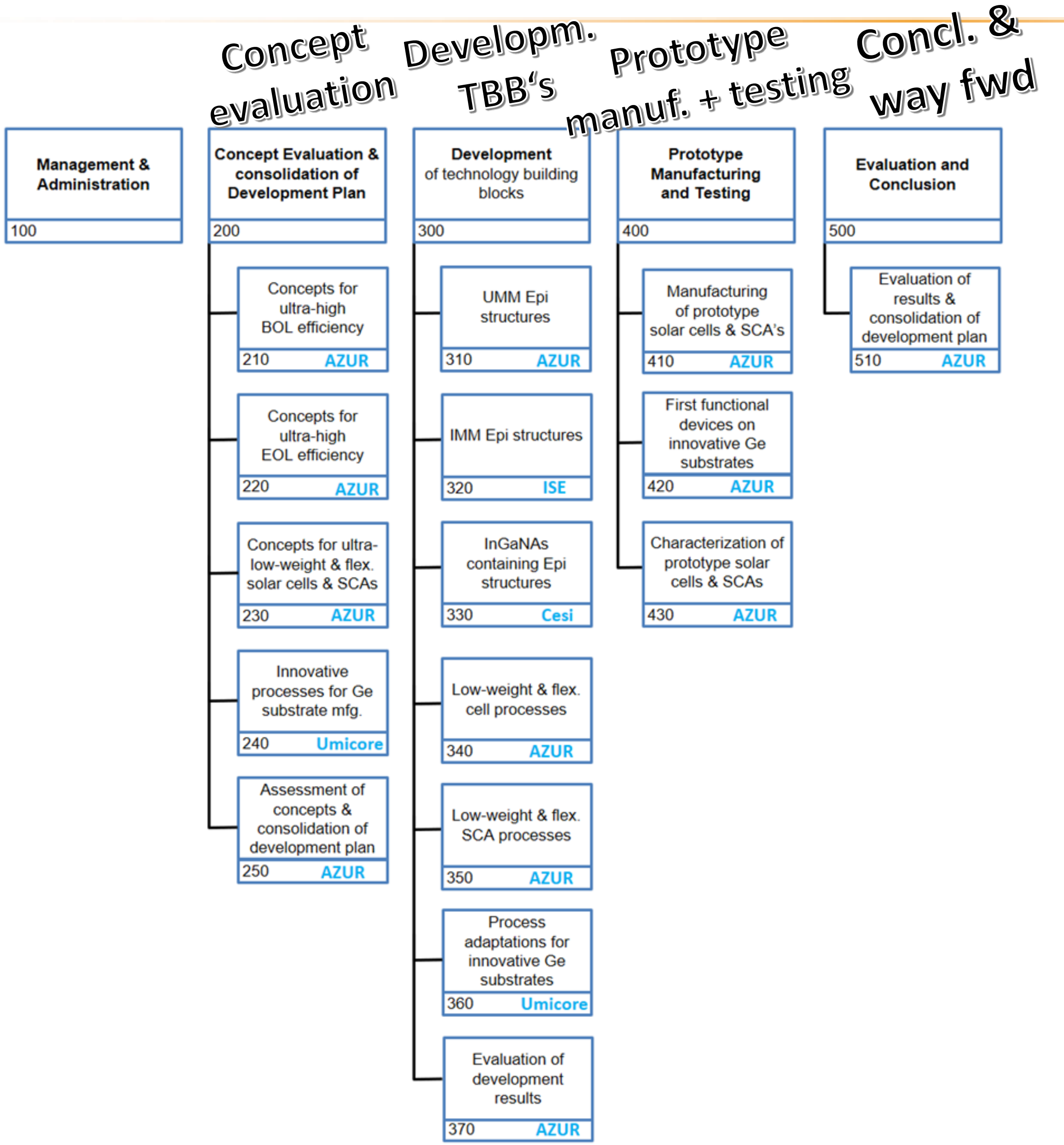

Work Share:

AZUR:

- BOL: 4J adaption on 4G32 basis
- EOL: Buffer+isotype (for future UMM cell)
- Ultra-thin cells targeting 20 mg/cm²
- thin & flex. SCA's

ISE & TF2:

- BOL: 4J-IMM
- ISE: IMM epitaxial growth & Characteriz.
- TF2: ELO + IMM cell process & Characterz

CESI & TAU:

- EOL: 4J EOL using InGaNAs on Ge
- CESI: Ge junction (MOVPE)
- TAU: InGaNAs growth (MBE)
- CESI: 2J ‚overgrowth' (MOVPE)

Umicore:

- Innov. substrates for CESI, ISE & AZUR

Project overview – schedule / Gantt Chart

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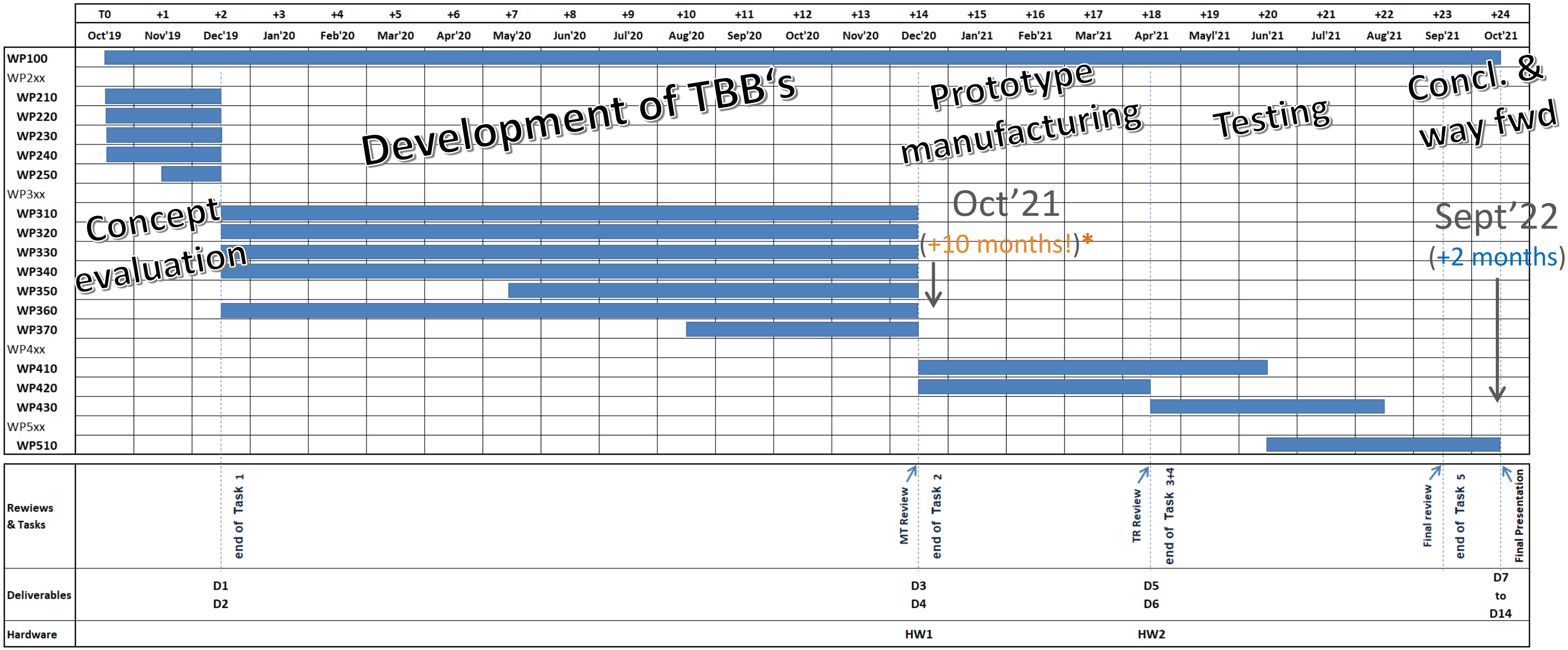

*) significant delays; mainly due to:

- COVID-19 pandemic measures; e.g. limited access to lab's, lockdowns
- Technical issues; e.g. reactor contamination

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➢ Overview on Deliverables & HW:

Deliverables		Status
D1	TN1: Assessment of the different solar cell concepts	✓ Dec'2019
D2	DP1: Development Plan for technology building Blocks	✓ Dec'2019
D3	TN2: Achievement report on technology building blocks	✓ Oct'2021
D4	TR1: Irradiation test report on selected component cells	✓ together with FR
D5	TP1: Test plan for engineering model tests	✓ together with FR
D6	TR2: Test report on engineering model tests including the analysis of data	✓ together with FR

Deliverables		Status
D7	DP2: Development plan for further optimization on investigated solar cell concepts	✓ together with FR
D8	TDP: Technical data package (including all deliverable documents)	✓
D9	FR: Final report (public)	✓
D10	ESR: Executive summary report (public)	✓
D11	AB: Abstract (public)	✓
D12	TAS: Technology achievement summary	✓
D13	FP: Final presentation	(✓)
D14	CCD: Contract closure Documentation	✓

Hardware		Status	Description
HW1	Component cells for irradiation testing	✓	As a minimum 10 pcs per new semiconductor material
HW2	Solar cell prototypes	✓	As a minimum 50 pcs per concept selected:

- ✓ Submitted / finished
- ✓ (yellow) Ready; in approval loop (not subm.)
- ✗ pending

Technology Building Blocks

AZUR – Part 1:
Buffer for UMM EOL concept

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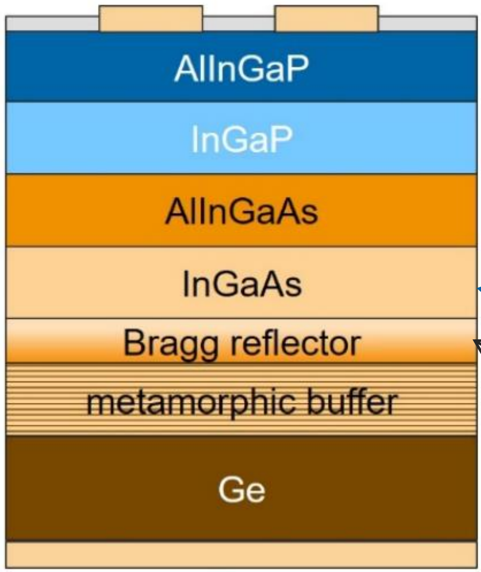
Background on potential novel UMM cell concept:

Impro-33

1st step: new buffer structure with increased In content; increased lattice constant



Still needed for full cell structure:

New sub-cell materials (partly quaternary & Al containing)

New tunnel diodes

Already tested to demonstrate buffer feasiblity

New Bragg reflector with adopted Lattice constant

Calculated max. efficiencies:	BOL: 34.4%
(EOL adapted to 1E15)	EOL: **32.7%**

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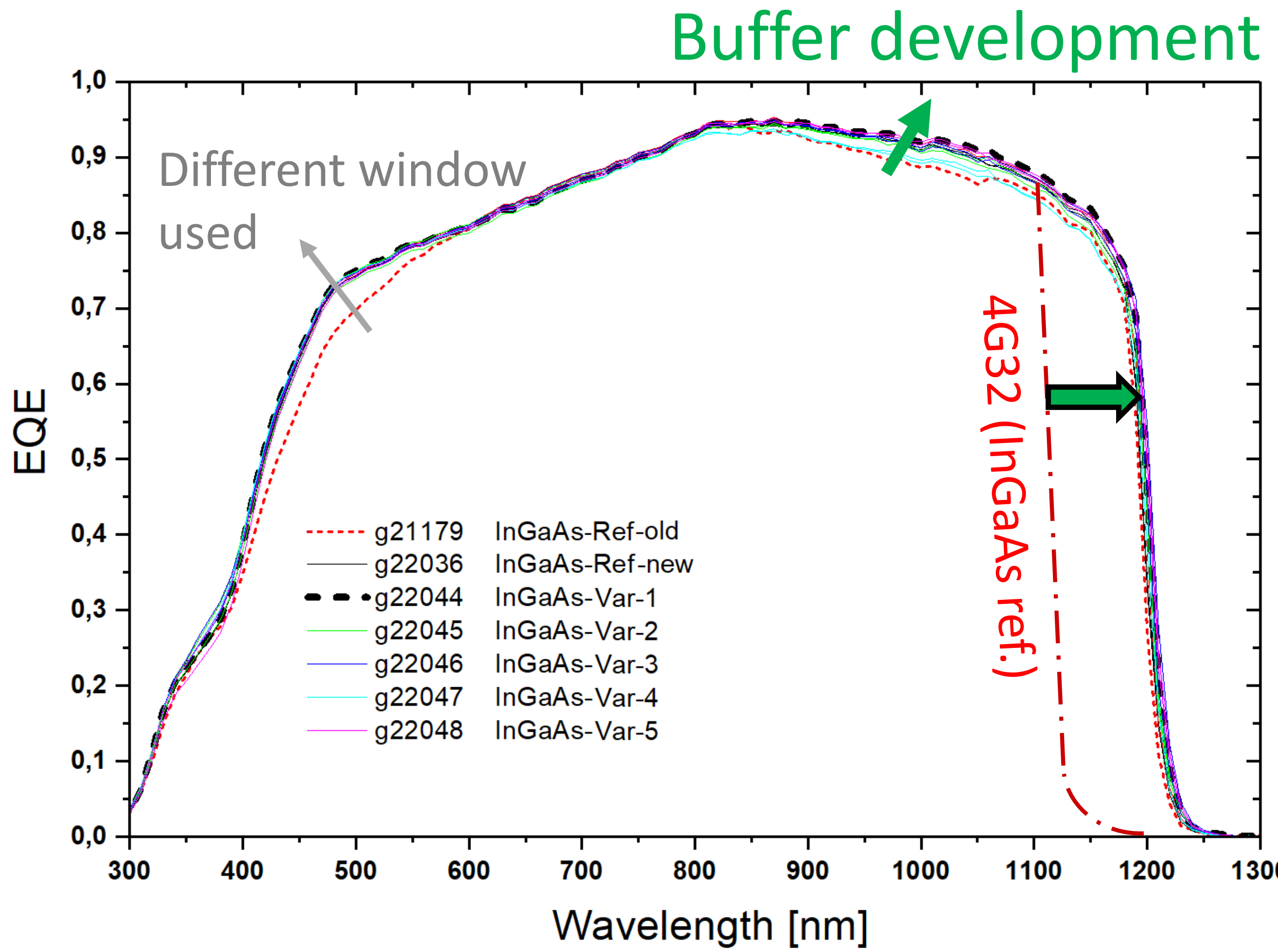
Final iteration on buffer for UMM EOL architecture incl. InGaAs isotype

→ EQE of isotype demonstrates that the needed band-gap shift is reached!

(EQE also is on high level, indicating good crystal quality)



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Irradiation tests on 2x2 cm² isotype InGaAs cells on new buffer

- Three irradiation doses tested: 1E15, 3E15 & 1E16 e-/cm² (1 MeV)
- Data analysis shows promising results
- But interpretation difficult:
  - Optically not filtered
  - Thick absorber
  - No DBR

Comparison to 4G32 InGaAs isotypes @1E15

	Reference isotype (4G32)	Isotype on new buffer (high In-content)	
Eg [eV]	1.10	1.02	
V_{OC} BOL [mV]	738	658	
W_{OC} [mV]	**362**	**362**	A)
V_{OC} EOL [mV]	591	542	
Delta $V_{OC,EOL}$ [mV]	147	116	
RF V_{OC} [%]	**80.1**	**82.4**	B)

*) Isotype on new buffer without optical filter; Ref. with opt. filter

A) Woc: Demonstrates same level of InGaAs material quality as 4G32 reference!
B) RF Voc: Indicates good (maybe better) radiation hardness for new InGaAs material

→ UMM buffer development for future UMM cell concept fully successful!

Technology Building Blocks

AZUR – Part 2:
4J-UMM with increased BOL eff.

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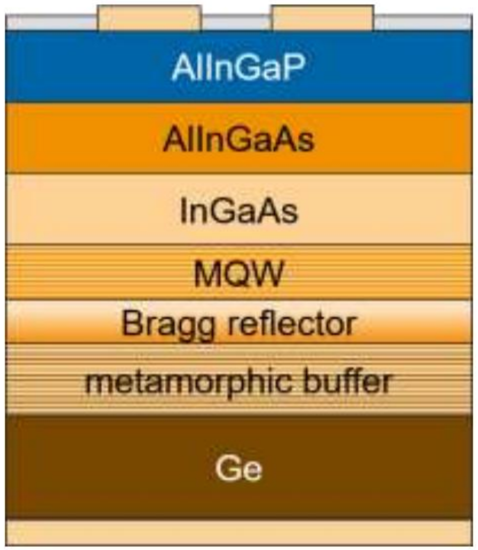
Background on Cell Concept:

Impro-33 Initial plan to improve 4J-UMM cell structure for BOL missions:
→ MQWs in InGaAs



Adopted during project progress:

Top- & Mid-cell thicknesses

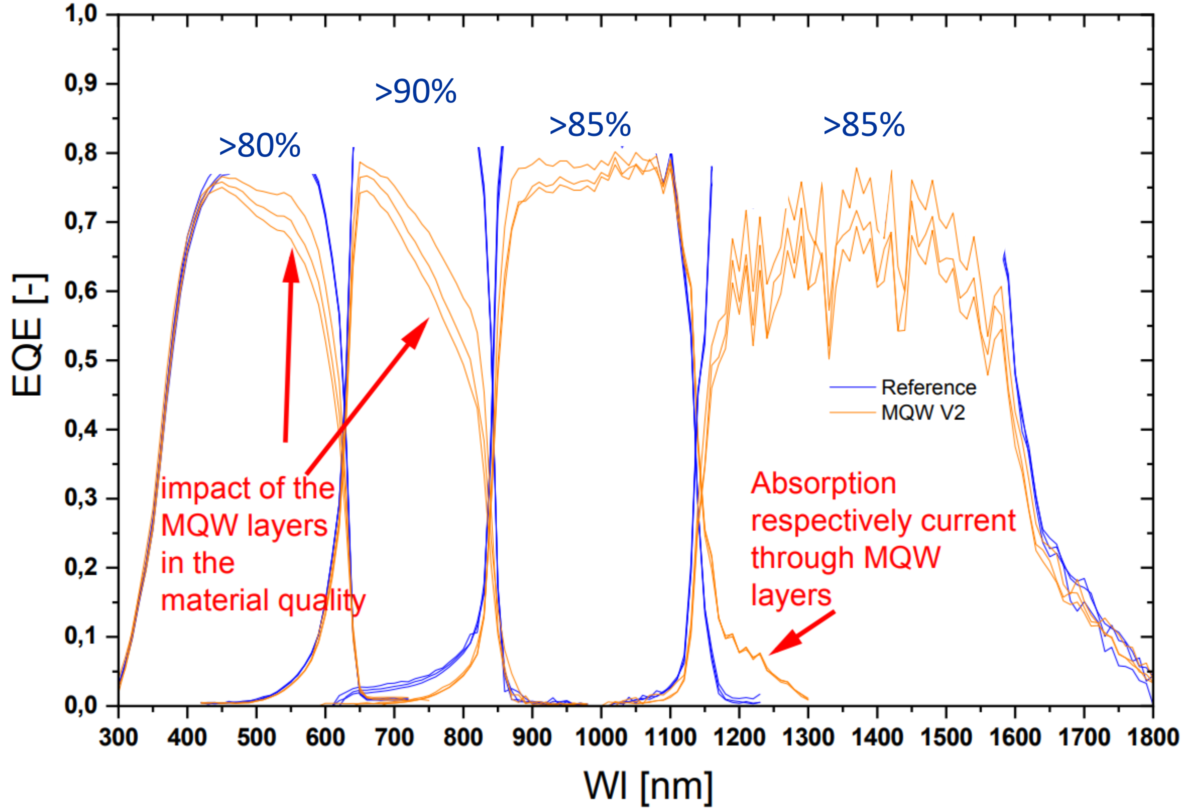
Band-gap tuning on top-cell material

Calculated max. efficiency: BOL: 34.9%

Several iterations with full 4J iteration with **MQW** structures in J3

- MQW's resulted in no improvement of the full 4J cell structure
  (upper cells are even affected)
- MQW's seem to become highly challenging & cost intensive

→ Therefore **MQW was not further pursued** in Impro-33 and **other options for BOL efficiency improvements were investigated**



(Best 4J-UMM-MQW cell achieved **29.4%**; 5x quantum wells)

Two further iterations focussing on current matching & band-gap tuning

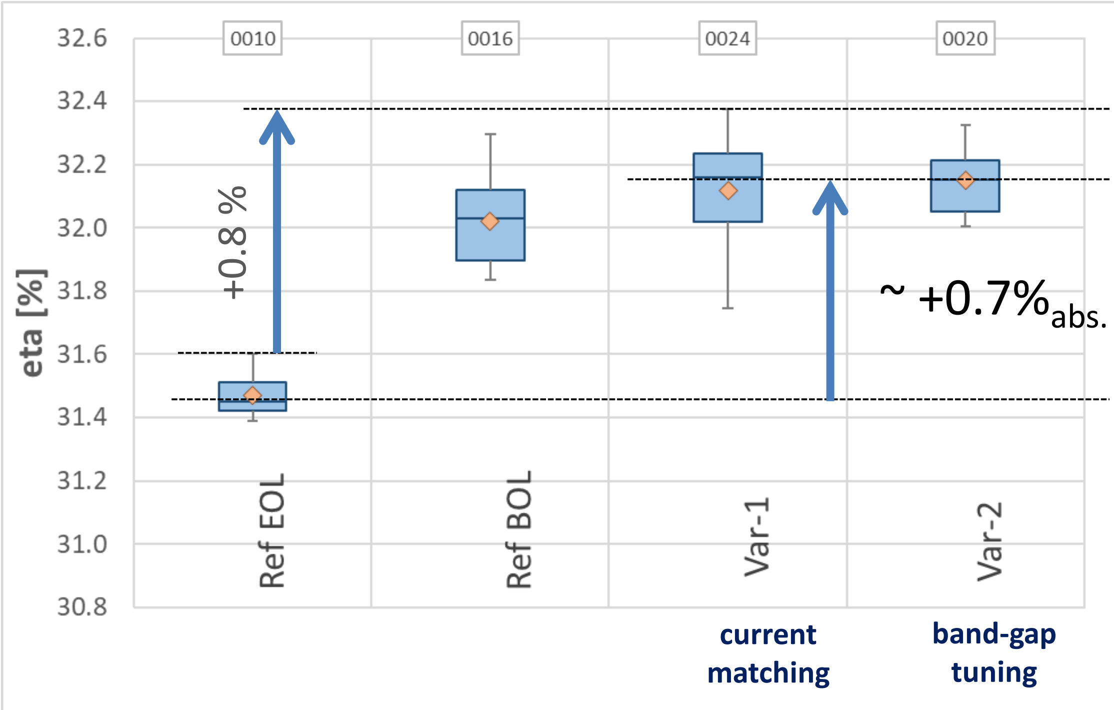
→ Required BOL eff. of 30% met; max.: **32.4%** ✓

→ Targeted BOL eff. of 35% not reached ✗

Note: 4G32 reference also below-avg. performance!

→ Estimated potential: **up to 33.5%**

→ Both approaches result in almost same BOL improvement



Irradiation tests to check feasibility for LEO missions (low doses)

- 1E14 & 2.5E14 e^-/cm^2 (1 MeV) tested
- Photon-annealing according to ECSS
- BOL **current matched type** seems more radiation tolerant than band-gap tuned cell

Dosis: 1.0E14	Current matching	Band-gap tuning
RF (Isc)	99.5%	99.0%
RF (Voc)	97.5%	97.5%
RF (eta)	**96.6%**	96.0%

Δeta ≈ 0.6%

Dosis: 2.5E14	Current matching	Band-gap tuning
RF (Isc)	98.3%	97.7%
RF (Voc)	96.0%	96.0%
RF (eta)	**94.0%**	93.4%

Δeta ≈ 0.6%

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AZUR – Part 3:

Low mass & mech. flexible cells and SCA's (Ge based)

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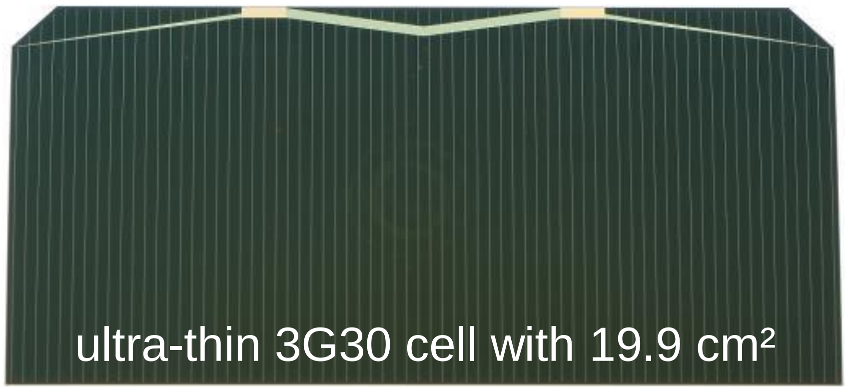
Ge based **bare solar cells** (by Ge thinning)

- Using a special grinding technique resulted in very thin and low-weight 3G30 solar cells with comparable efficiency as non-thinned references

- The targeted area related mass of **20mg/cm²** is achieved! ✅

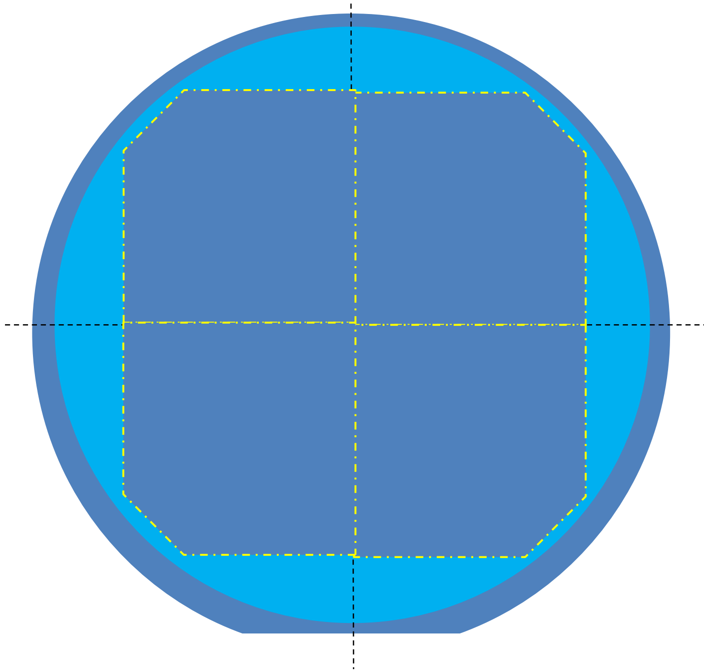


η_{avg} = **29.0%** (AM0, 1367 W/m², 25°C)

- As this grinding technique is compatible with AZUR's Ge recycling technology, at high production yield also **attractive costs** seem possible!

Ge based **bare solar cells** (by Ge thinning)

- For the final prototype batch a new cell design with improved wafer utilization was implemented (wafer utilization: approx. 63%)
- Four cells per wafer (A_{Cell} = 27.6 cm²)
- One cropped corner for std. Si-bypass diode allows very high PV ultilization on panel level (>95% possible)



TBBs – Part 3 // Low weight & flexible bare cells & SCA's (WP340)

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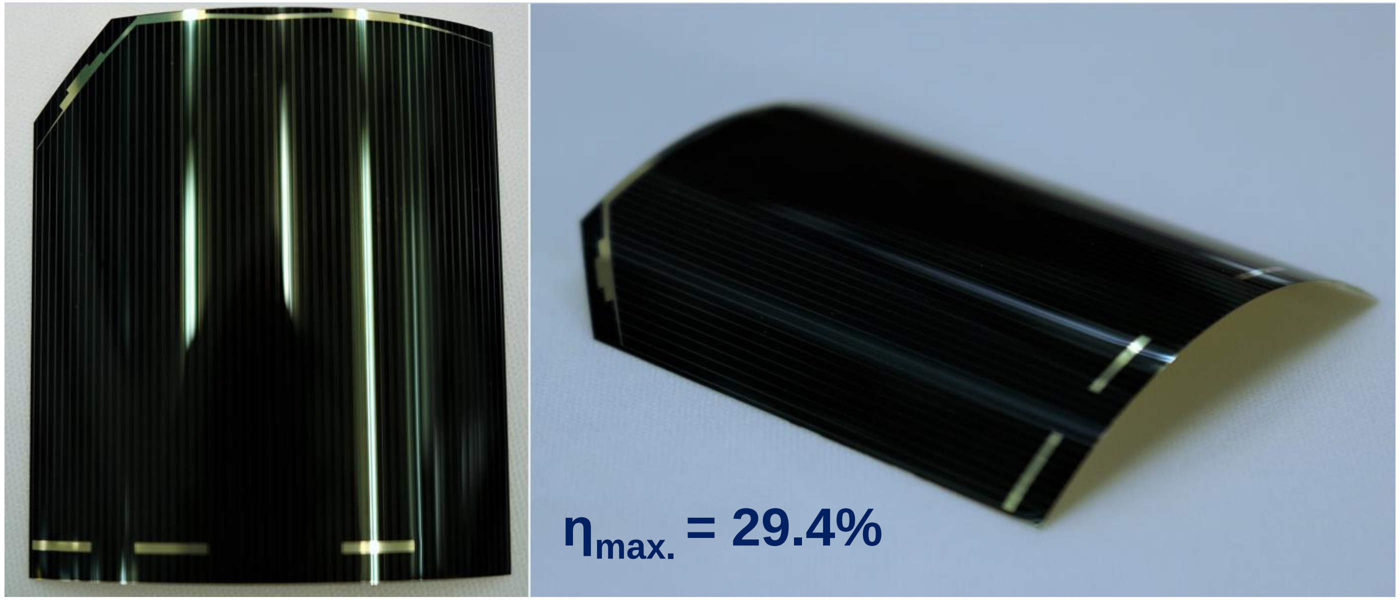
Ge based **bare solar cells** (by Ge thinning)

- With the final batch even ~19 mg/cm² was achieved on bare-cell level!
  (hero cell → 519 mg / 27.61 cm² = **18.8 mg/cm²**)



- Initially high cell bow was observed
- Finally a soulution was identified to significantly reduce the bow!

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Irradiation test on Ge based **bare solar cells**

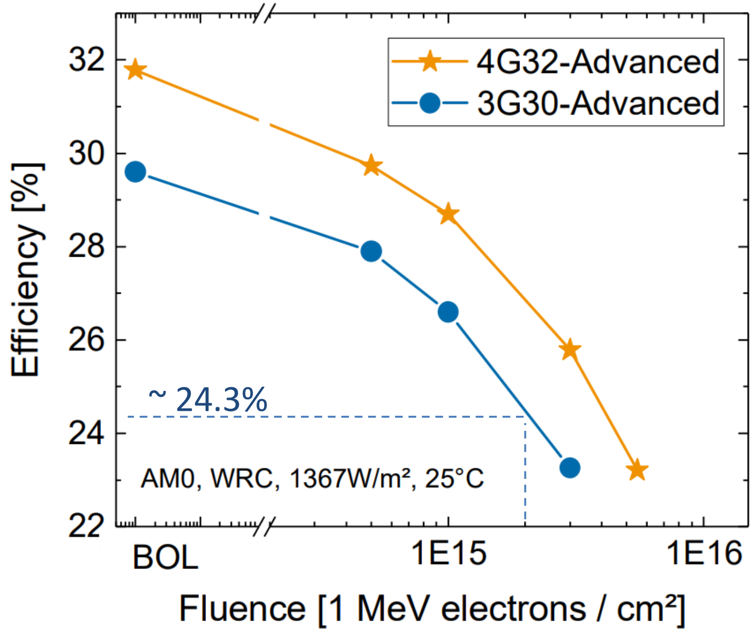
➢ BOL and EOL (2E15) characterization on ultra-thin bare cells:

BOL

sample No.	Isc [mA]	Voc [V]	Imp [mA]	Vmp [V]	Pmp [mW]	FF [-]	eta [%]
#01	484	2.671	471	2.356	1,109	0.857	29.4
#02	484	2.667	467	2.348	1,096	0.848	29.0
#03	484	2.671	469	2.358	1,106	0.856	29.3
#04	485	2.671	470	2.360	1,109	0.857	29.4
#05	483	2.674	469	2.362	1,107	0.857	29.3
#06	484	2.675	470	2.364	1,110	0.857	29.4
#07	483	2.670	469	2.363	1,107	0.858	29.3
#08	484	2.673	470	2.367	1,112	0.860	29.5

EOL 2E15

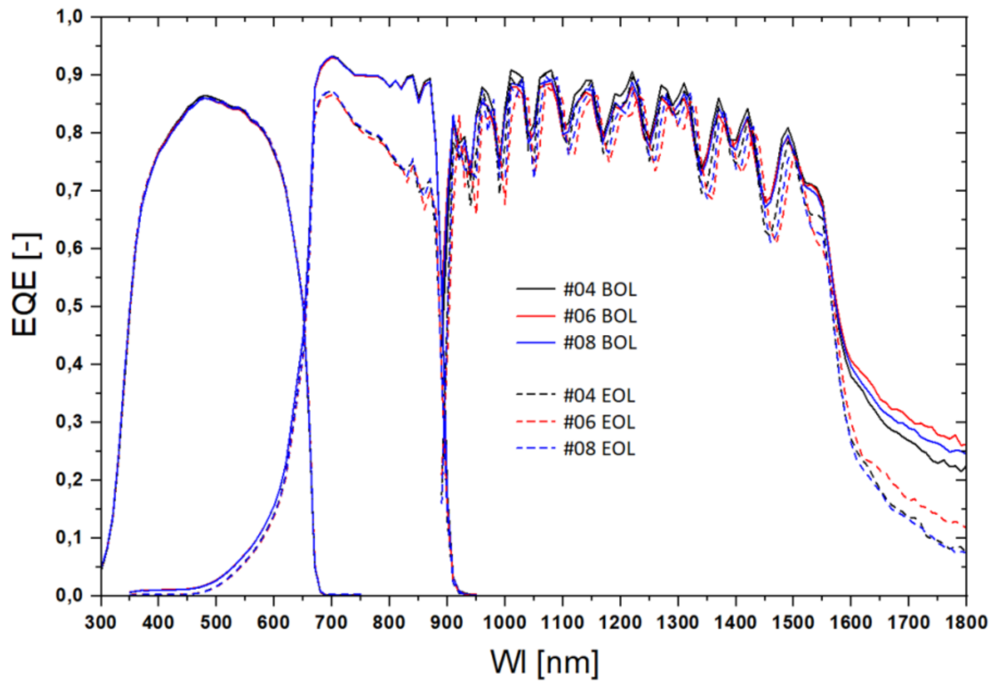
sample No.	Isc mA	Voc V	Imp mA	Vmp V	Pmp mW	FF	eta %
#04	440	2.324	408	2.002	816	0.797	21.6
#05	431	2.410	398	2.114	841	0.810	22.3
#06	434	2.366	403	2.041	822	0.800	21.8
#08	432	2.414	400	2.122	850	0.815	22.5



➢ EOL efficiency approx. 1.9%$_{abs.}$ lower than expected @2E15 for 3G30

Ge based **bare solar cells** (Ge thinning)

- EQE indicates that Ge cell still has excess current
- Indeed a lower QE at >1600nm is observed → rear mirror/pass. gets feasable!



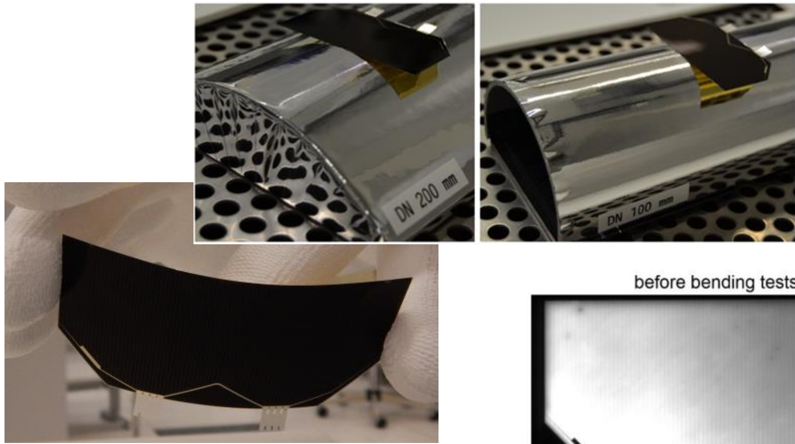
- Difference mainly due to lower FF than expected (RF_{FF}: ~95% instead of ≥97%)

Flexible **Solar Cell Assemblies** (SCA's)

- 50 µm cover glasses attached to 50 µm cells:

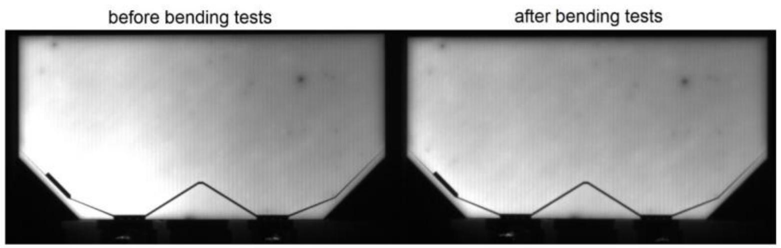
Table 1: mass of 6 samples manufactured

Sample	Total mass [mg]	mass/area [mg/cm²]
1	1565	51.9
2	1533	50.8
3	1531	50.7
4	1536	50.9
5	1534	50.8
6	1530	50.7



R_{bend} = 50 mm

→ **Flex. SCA!**



- Approx. **50 mg/cm² achieved on SCA level** (!)
- Compared to std.-SCA (non-thinned cell + 100 µm glass: ~115 mg/cm²)
  → **mass reduction of -56%**

Technology Building Blocks

Fraunhofer ISE & tf2 devices

IMM technology; epitaxy & cell processing

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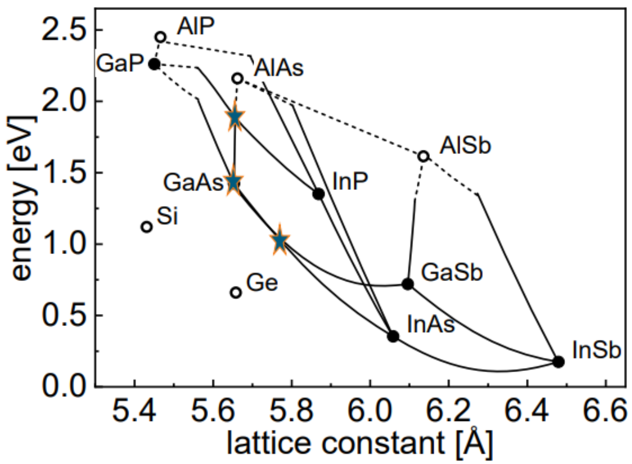
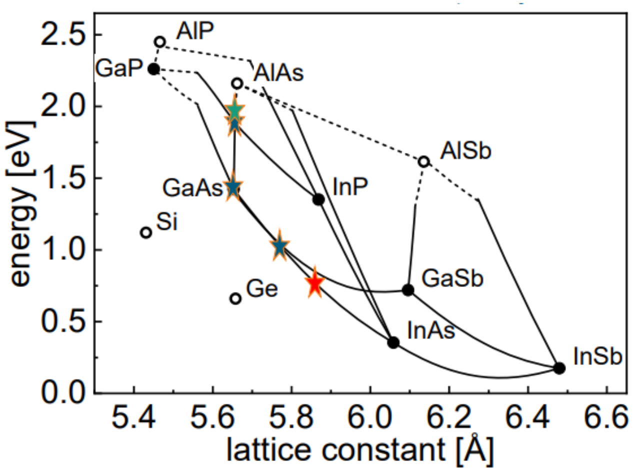
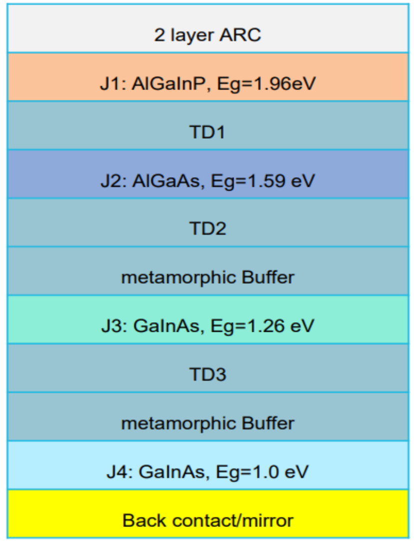
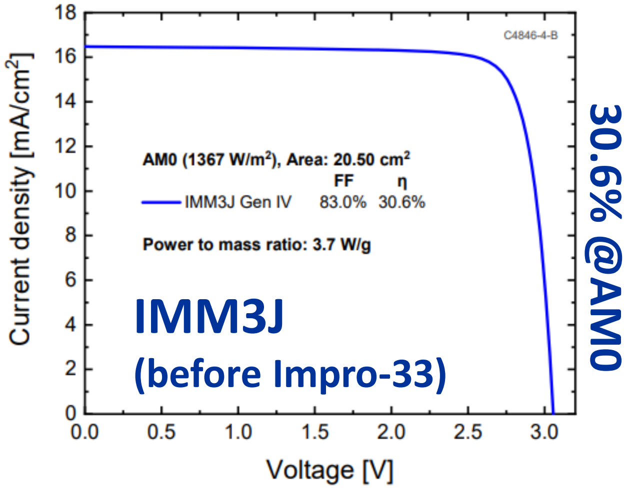
Fraunhofer ISE

Status before project (3J-IMM) and way forward to 4J-IMM



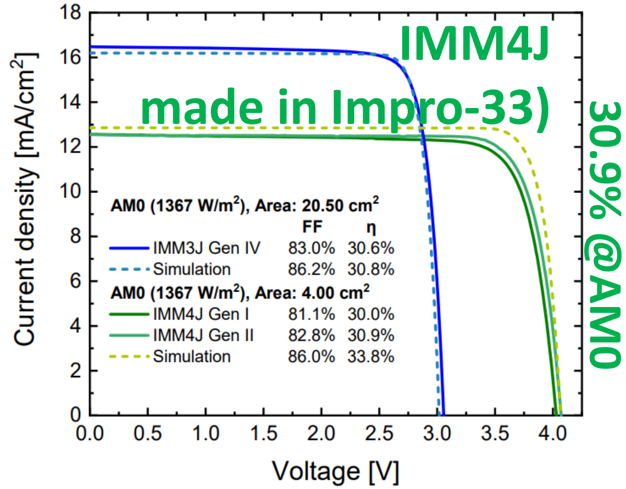




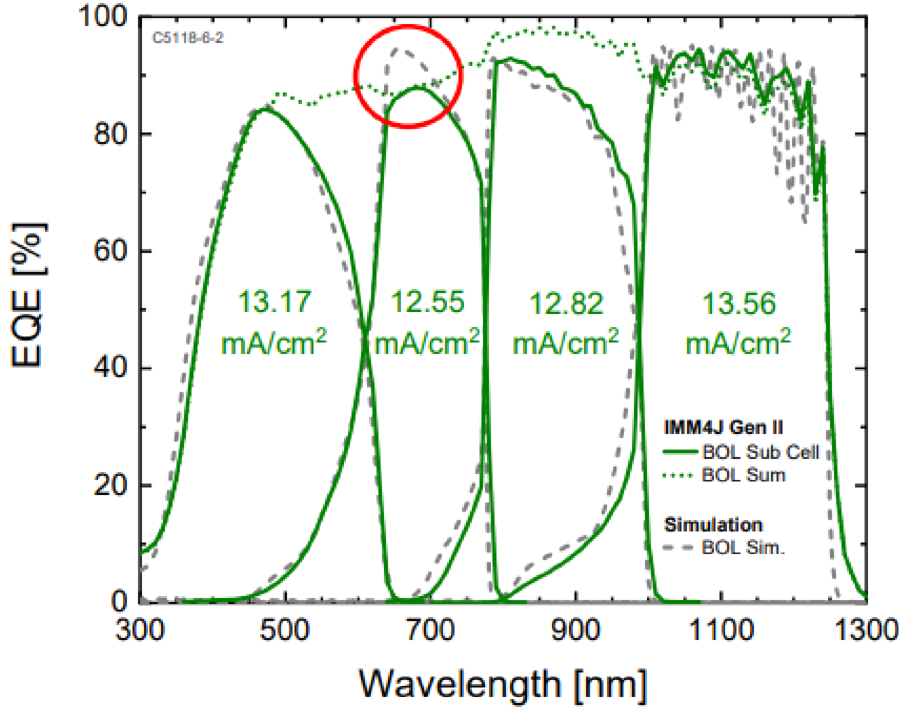


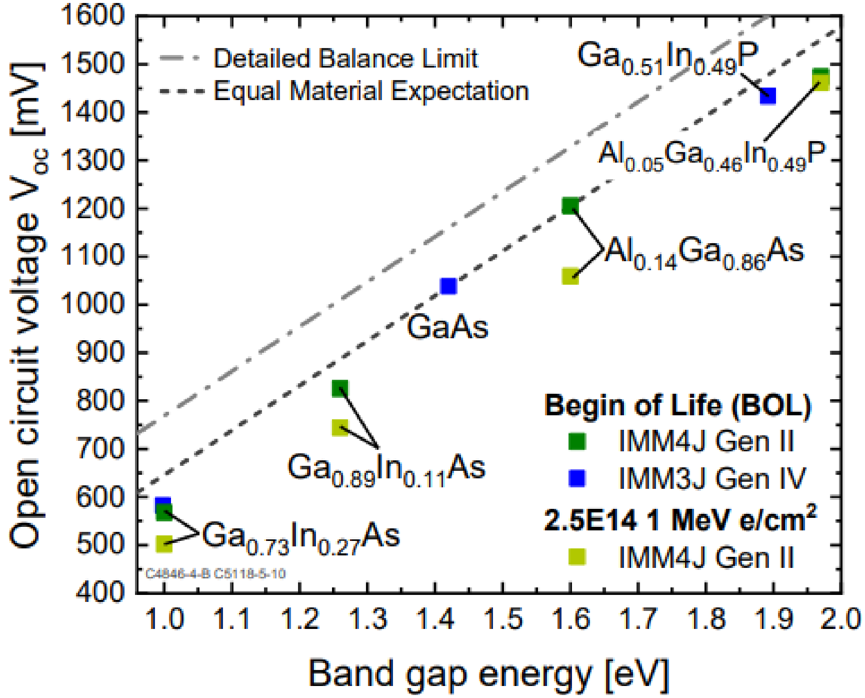
Two options:

- Increase top Eg
  + paves way for IMM5J
- Decrease bot Eg
  - significantly thicker
  - InGaAs less rad.-hard



New 4J-IMM with 30.9% AM0 eff. & V_{oc}= 4.07 V achieved!



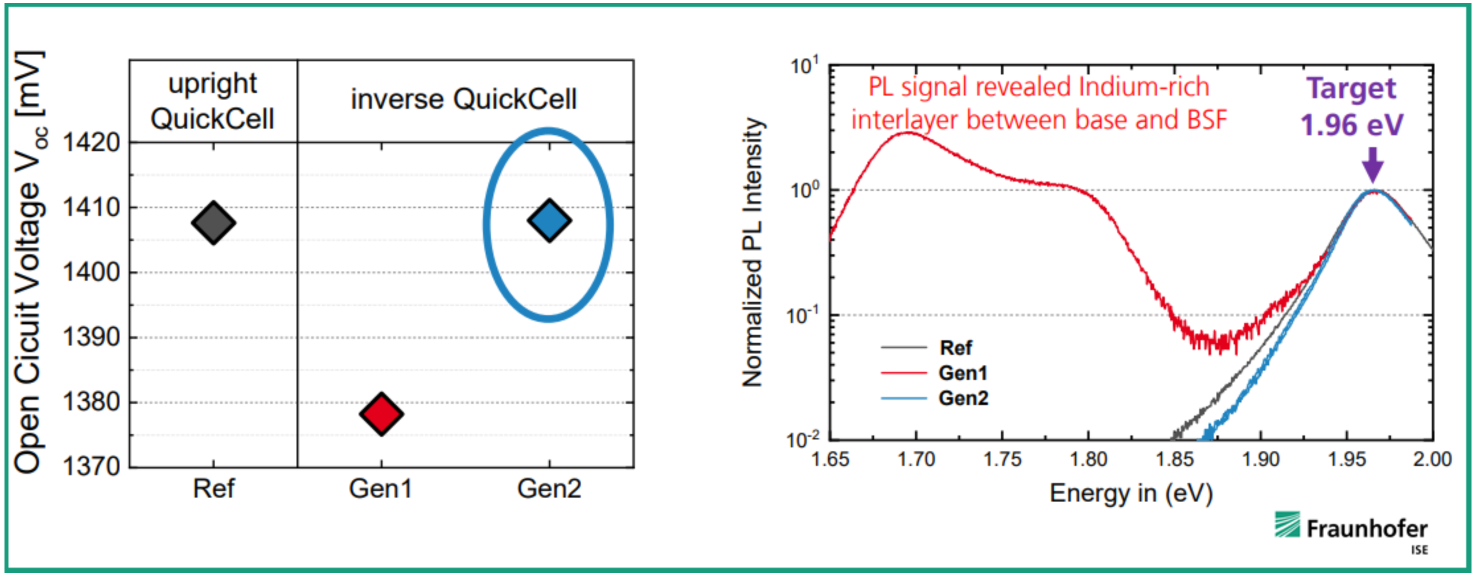


- J2 limits the current but has high material quality (+0.5% power)
- J3 & J4 can be further optimized appox. +70 mV (+2% power)
- Improved current matching → +0.4 mA/cm² (+3% power)
- FF improvement (82.8%) of apprx. +4% possible (+4% power)

} η_{BOL} potential up to **~33.8%**

An inv. 'Quick Cell Process' for inv. epi was developed at ISE

- Target: Feedback within days for development on V_{OC} & E_g
- Reduced process effort: RS mtetal / ELO / FS metal (no ARC, no MESA)
- Example (inv. AlInGaP cell; J1 in 4j-IMM):



- Summary: i-QCP successfully implemented
- But processing not stable enough yet → further development needed

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tf2 devices

Final Presentation 13-10-2022 (ESTEC/online)

Impro33
Improved multi-junction solar cells with up to 33% eff. at end of life
tf2 devices contribution

ESTEC Contract No. 4000128123/19/NL/FE

Introduction

- Back reflector improvement
- IMM cell processing
- Ultra-thin IMM4J solar cells development
- Ultra-thin IMM4J engineering test samples
- Ultra-thin IMM4J solar cell tests

Back reflector improvement (1)

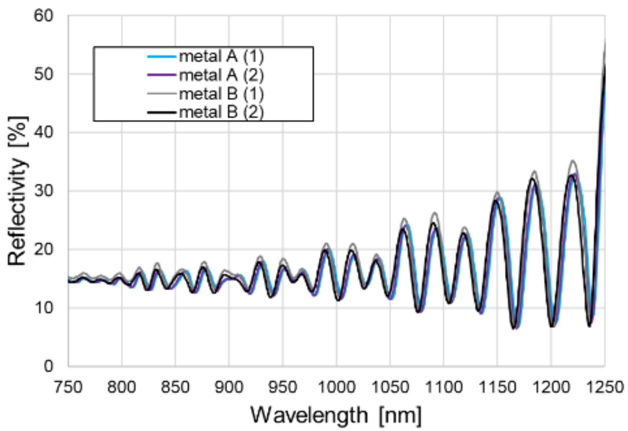
- Ultra-thin (IMM) solar cells can be equipped with efficient back reflector.
- Reflects photons that can then:
  - $E_{ph} > E_g$: be absorbed (improving Jsc, Voc).
  - $E_{ph} < E_g$: leave cell (reducing cell temperature).

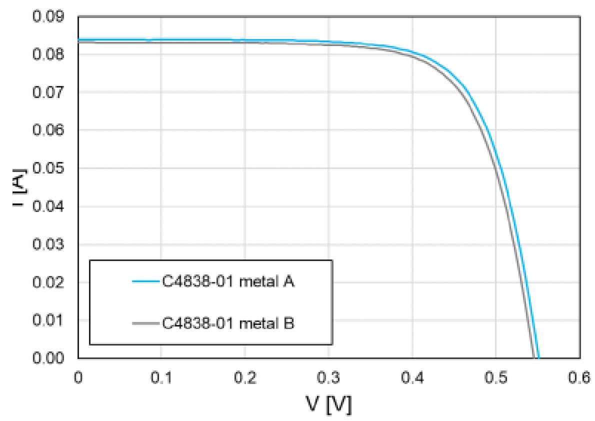
- Studied several methods to improve performance of *tf2* back reflector:
  - Other reflector material.
  - Introducing dielectric intermediate layer.
  - Texturing back reflector.

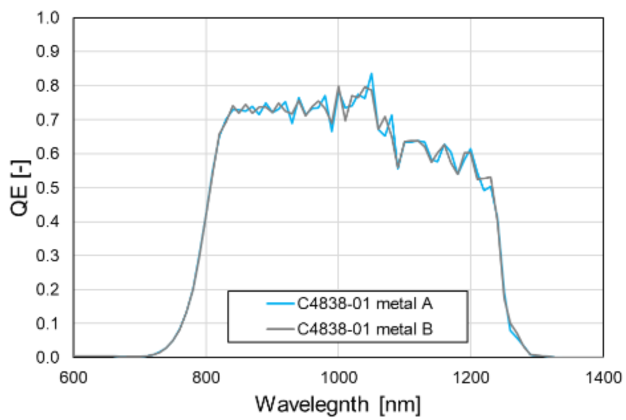
Back reflector improvement (2)

Other reflector material

- Performed 'direct comparison' between standard reflector metal (A) and metal with better reflection (B) (in theory). ISE IMM1J test structure.
- Contrary to simulations no significant improvement observed, neither in reflectivity, IV or EQE.



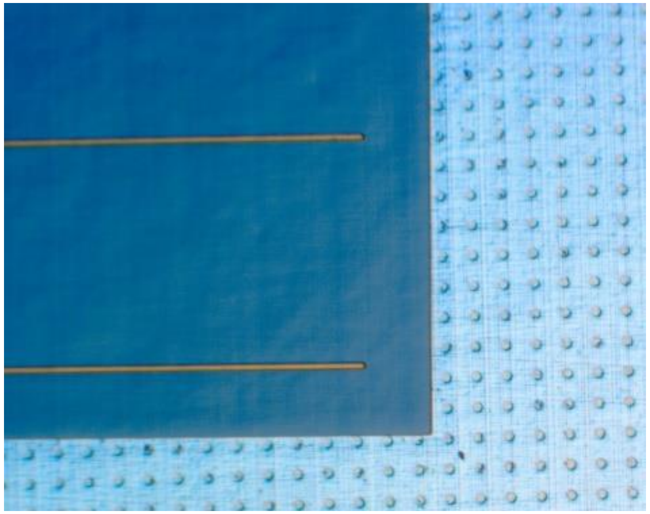


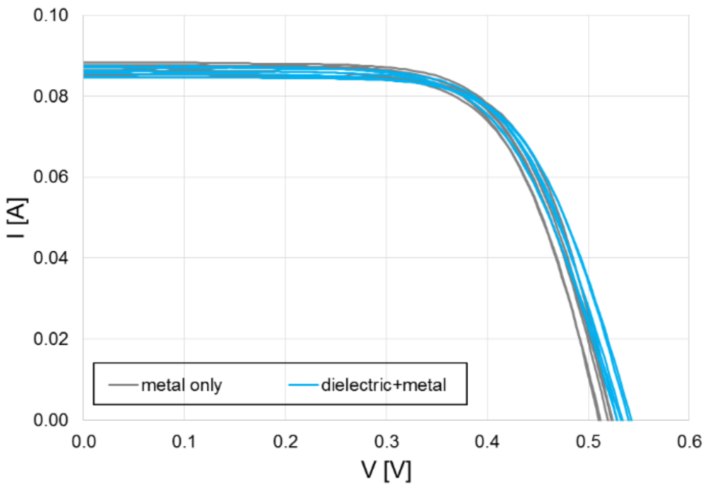


Back reflector improvement (3)

Dielectric intermediate layer

- Performed 'direct comparison' between standard reflector and version with dielectric layer in between semiconductor and metal. ISE IMM1J test structure.
- Vias ensure electric contact.
- Dielectric on average 15 mV higher Voc, Jsc marginally higher. FF slightly reduced (via contact area only 55%).
- Further research should focus on:
    - Comparison different types of dielectrics.
    - Improving vias coverage and design.

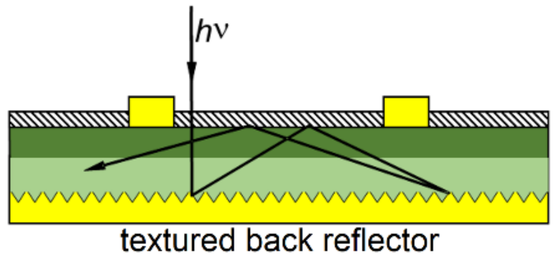


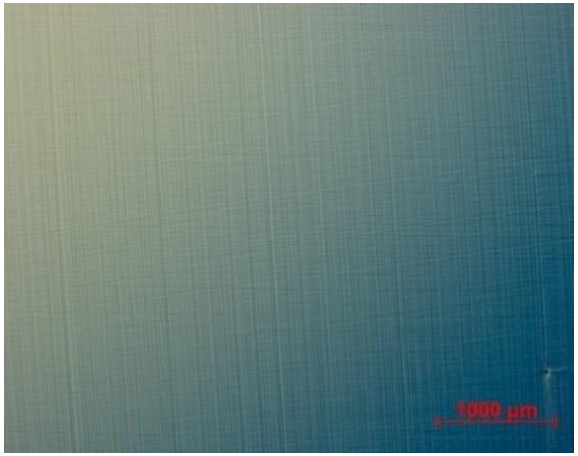


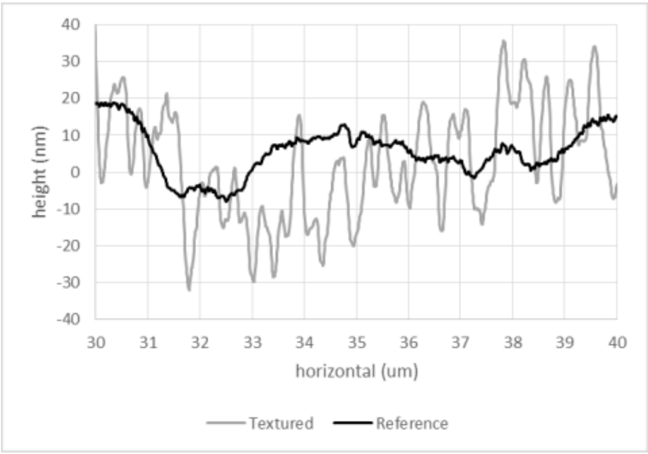
Back reflector improvement (4)

Textured back contact

- Light reflected from a textured back reflector is scattered.
  - Increases pathlength through absorber → higher absorption probability.
- IMM epi-structures already display non-planar back sides, still worthwhile to test whether improvements can be made.
- Technique already demonstrated on GaAs solar cells with AlGaAs back contact epi-layers [1].
- IMM cells have AlGaInAs back contact layer.
- Successful texturing etchant found that increases roughness.
- More research required to incorporate into actual solar cells.







[1] van Eerden M., et al. IEEE 46th PVSC (2019) 2637.

IMM cell processing

tf2 devices

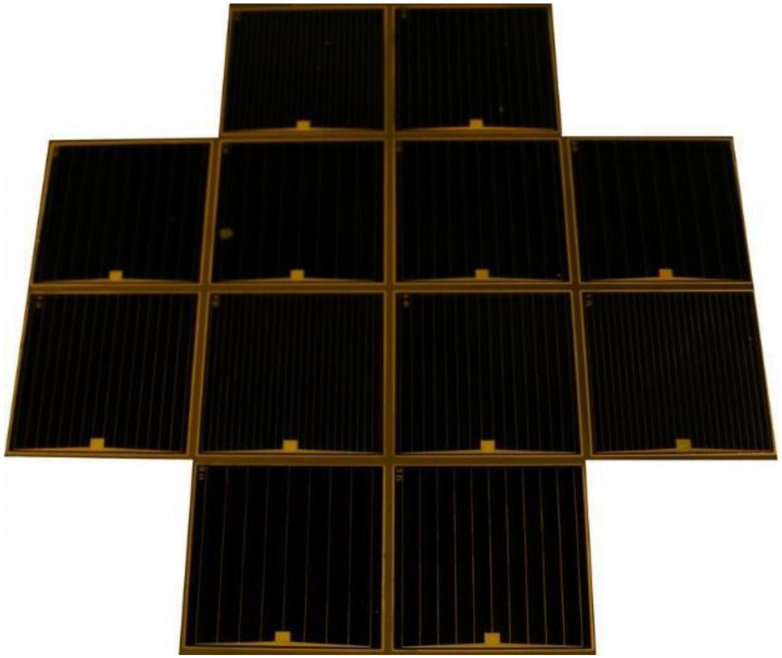
- Wet mesa etch used to define solar cell boundaries and electrically separate neighboring solar cells.
- Good mesa etch should:
  - Have moderate etch rate ✓✓✓
  - Etch uniformly ✓✓✓
  - Be reproducible ✓✓✓
  - Not affect photoresist ✓✓
  - Not affect the back contact ✓✓
- Aim: improve existing *tf2* mesa etch procedures and tune towards IMM4J.

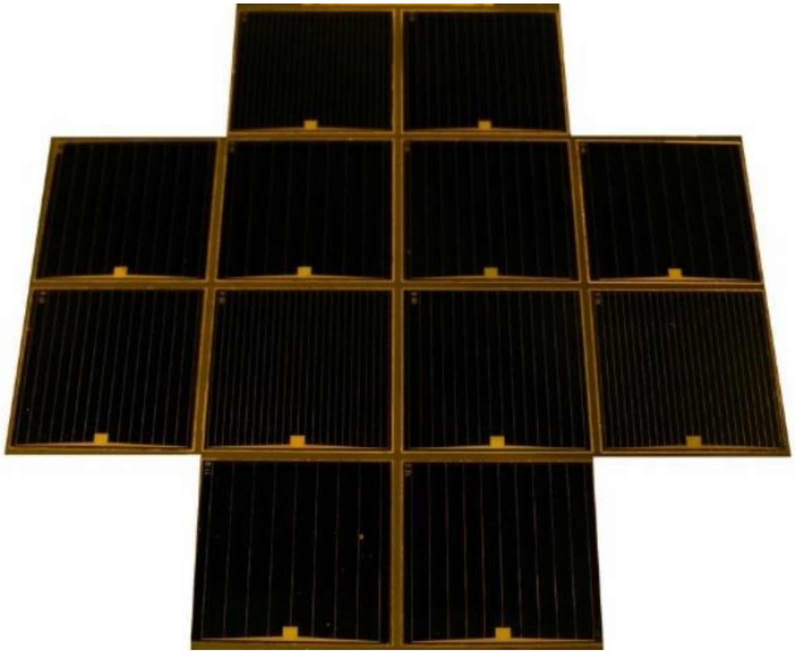
- Result: IMM1J mesa etch procedure with improved compromise between requirements.

- Further adapted to IMM4J structures. Positive effects illustrated by ultra-thin IMM4J solar cells' good performance, yield and reproducibility, typically uniform over 4-inch film.

Ultra-thin IMM4J solar cells (1)

- Arrays of BOL and EOL design 2x2 cm^2 IMM4J cells manufactured (ISE epi).

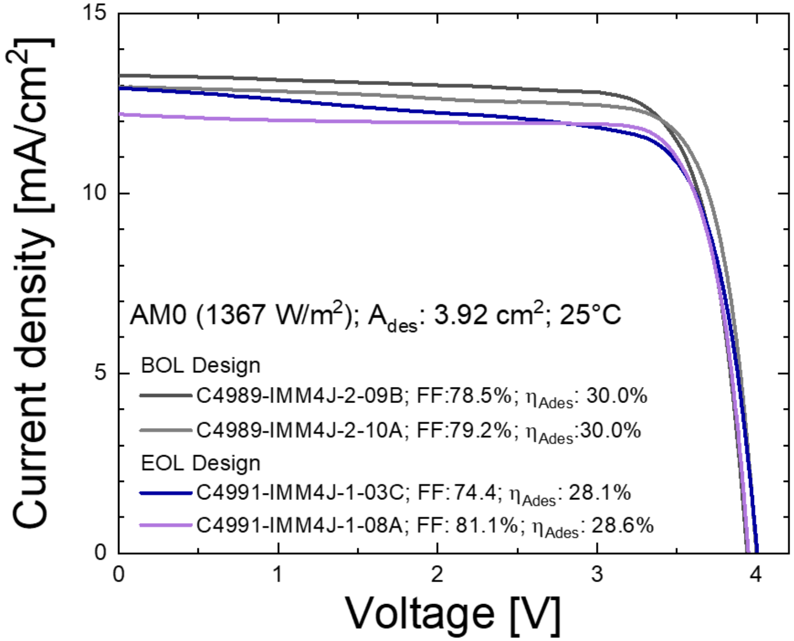


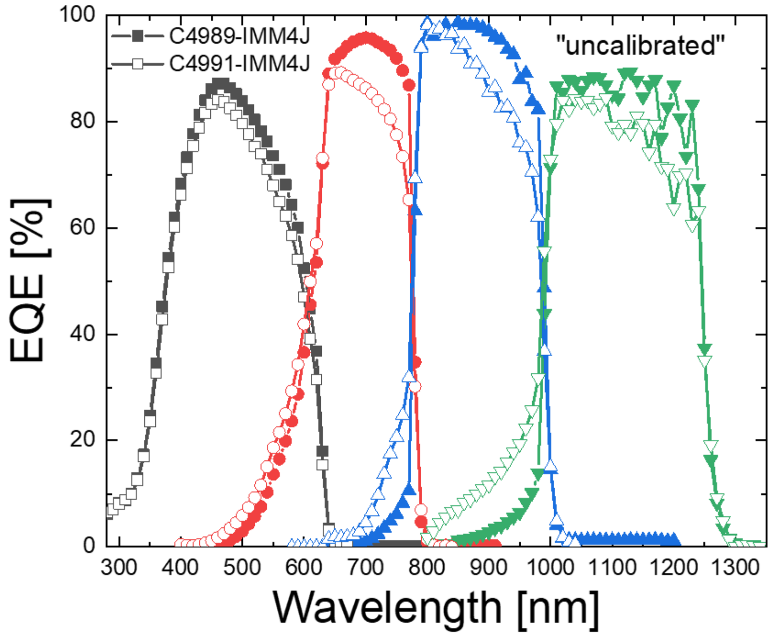


Ultra-thin IMM4J solar cells (1)

tf2 devices

- Selection of IMM4J cells characterized by ISE CalLab.



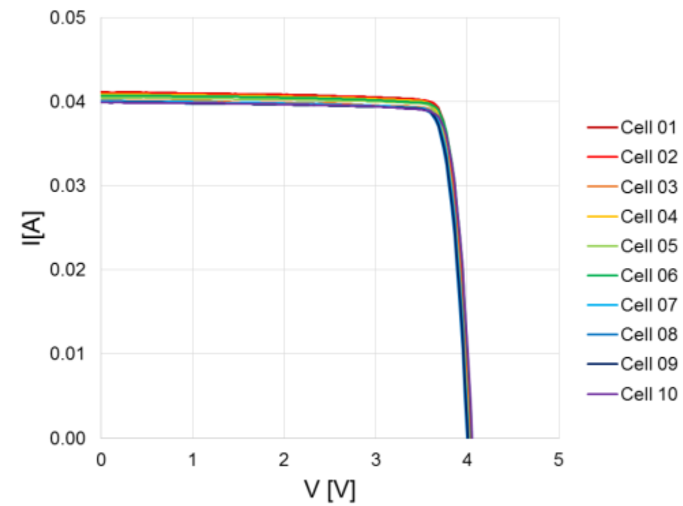


- Efficiencies achieved (for designated area*, A_{des}):
  - BOL design: 30.0%.
  - EOL design: 28.6%.

* Designated area, A_{des}(3.92 cm^2) := aperture area (3.99 cm^2) – busbar area (0.07 cm^2).

Ultra-thin IMM4J test samples (1)

- Manufacturing stage: processing of ultra-thin IMM4J solar cells was further refined.
    - Resulted in efficiency increases:
        - BOL design: 30.0% designated area → 30.0% full area.
        - EOL design: 28.6% designated area → 28.9% full area.
- Further efficiency improvement achieved with new ISE IMM4J epi-wafer batches (BOL).
- 60 pc 2x2 cm^2 ultra-thin IMM4J solar cells manufactured.
    - >40 pc with $\eta > 30\%$, acc. to *tf2* indicative characterization.
    - Cell performance uniform over 4-inch films.

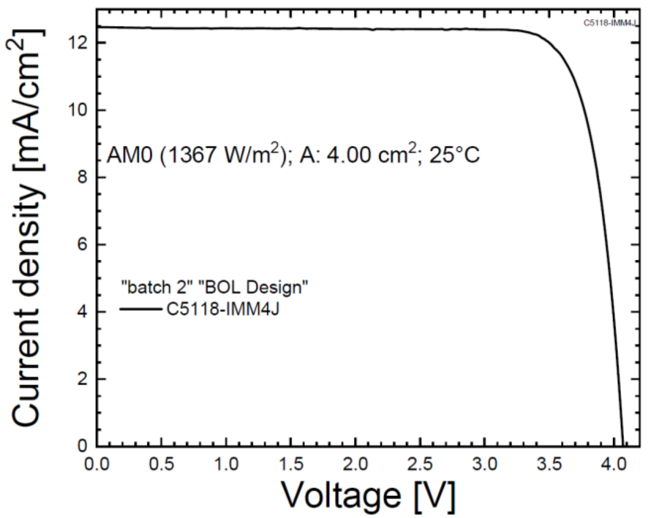


Ultra-thin IMM4J test samples (2)

tf2 devices

- 15 IMM4J cells characterized at ISE CalLab.
- Efficiency 30.9% (full area) achieved.

- Together with low mass of the ultra-thin cells
  - Required performances: all achieved.
  - Target performances: several achieved.

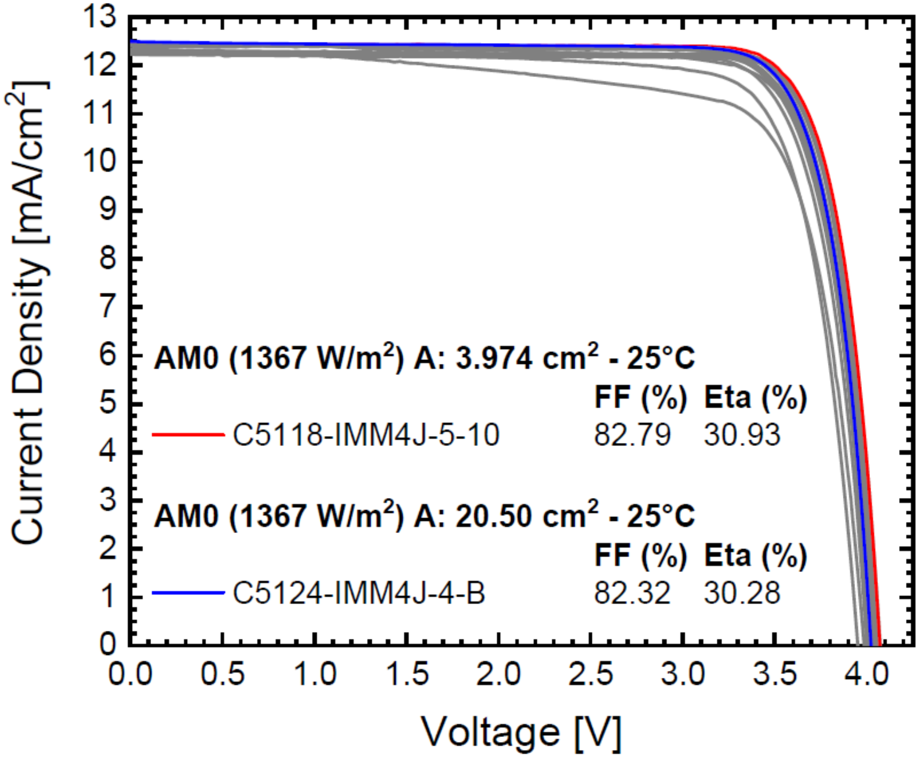


IMM4J cell (BOL)	η_{BOL} (full area) (%)	specific power (W/g)	areal mass density (mg/cm²)
Target performance (SOW)	>35.0	>2.39 ✓	<20.0 ✓
Required performance (SOW)	>30.0 ✓	>0.82 ✓	<50.0 ✓
Achieved (C5118-5-10)	30.9	3.00	14.1

Requires IMM5J structure
(Realistic potential IMM4J (ISE): 33.8%)

Ultra-thin IMM4J test samples (3)

- Also fabricated larger area (20.5 cm^2) IMM4J cell.
- Performance similar to best 2x2 cm^2 cell.
- Demonstrates feasibility of large area IMM4J cells.



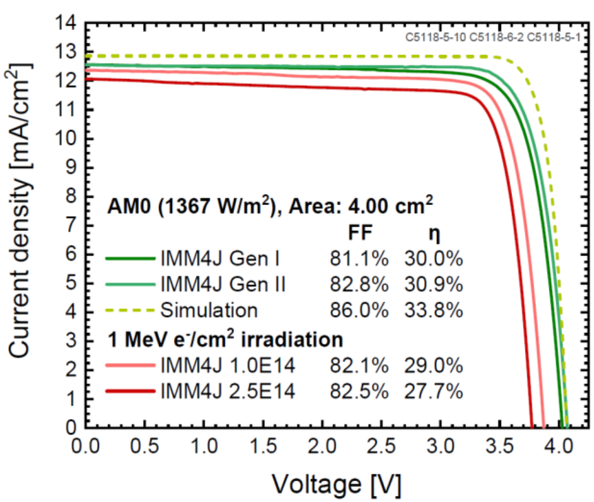
Ultra-thin IMM4J solar cell tests

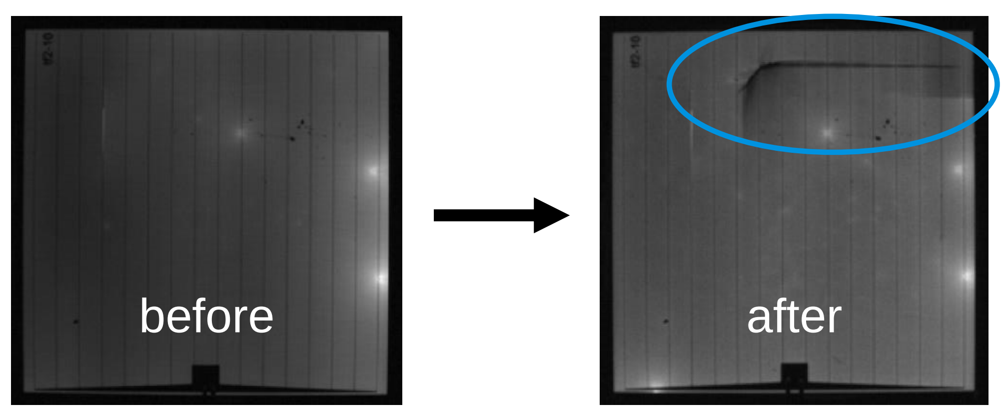
tf2 devices

- Temperature coefficient measurements (ISE).
  - IMM4J cell performance decreases (somewhat) less with increasing temperature compared to other 4-junction cell concepts.

	dJsc/dT ($mA/cm^2 \cdot °C$)	dVoc/dT (mV/°C)	dFF/dT (%/°C)	dEff/dT (%/°C)
IMM4J C5118-5-10	0.0038	-8.4	-0.038	-0.067
AZUR 4G32C	0.0175	-8.4	-0.026	-0.085
SolAero Z4J	0.0055	-9.0	-0.048	-0.071

- Low irradiation tests (1.0 and 2.5 E14 1 MeV e^-/cm^2) (AZUR).
  - Results distorted due to cell mishandling → temporary support development desirable.





Summary

- Several back reflector improvements tested, some promising.
- IMM cell processing improved.
- >60 pc 2x2 cm^2 ultra-thin IMM4J solar cells manufactured.
- 30.9% efficiency demonstrated for ultra-thin IMM4J solar cell.
  - Specific power: 3.00 W/g.
  - Areal mass density: 14.1 mg/cm^2.
- All required and even several target performances achieved.
- Large area feasibility IMM4J cells demonstrated.
- Development of temporary support desirable.

Technology Building Blocks

CESI
Shaping a Better Energy Future
&
Tampere University

InGaNAs cell technology;
MBE & MOVPE

AZUR SPACE
ENABLING TECHNOLOGIES

TBBs – 4J cells using InGaNAs cell technology

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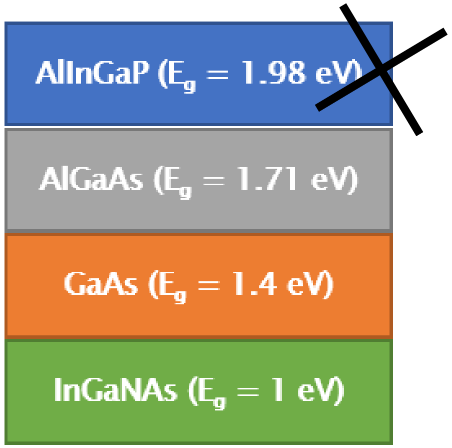
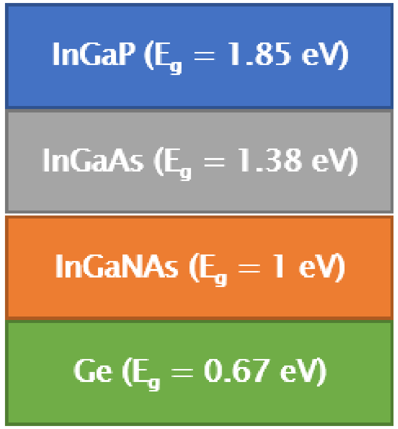
BOL concept



EOL concept



Predicted electrical performances

	BOL	EOL
Jsc (mA/cm²)	12.42	11.59
Voc (V)	4.464	4.16
FF	0.87	0.86
Eff. AM0@25°C	35.3%	30.2%

	BOL	EOL
Jsc (mA/cm²)	16.08	15.69
Voc (V)	3.379	3.367
FF	0.87	0.83
Eff. AM0@25°C	34.6%	31.9%

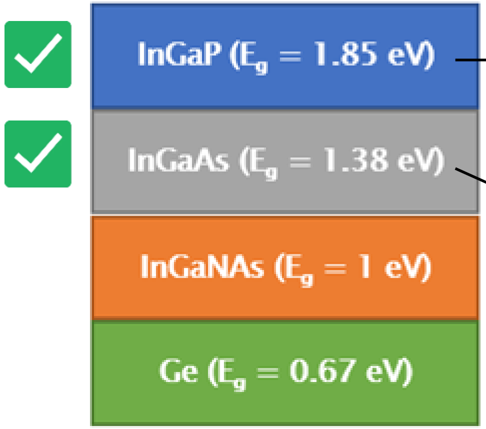
- AlInGaP isotypes showed very low performance compared to previous samples
- After deep investigation in May 2020 an with the hydrogen purifier was identified
- Due to the COVID-19 pandemic & difficulties in supplying chains, the purifier was replaced only in March 2022. <u>Therefore the BOL concept needed to be set on hold</u>.

TBBs – 4J cells using InGaNAs cell technology

AZUR SPACE
ENABLING TECHNOLOGIES

CESI
Shaping a Better Energy Future

EOL concept



Growth	Isc[A]	Jsc [mA/cm^2]	Voc[V]	F.F.	Eff.[%]
R6985	0.431	16.264	2.302	0.82	22.48
Theor.	0.427	16.100	2.508	0.84	24.86

Growth	Isc[A]	Jsc [mA/cm^2]	Voc[V]	F.F.	Eff.[%]
R6978	0.435	16.401	0.964	0.81	9.38
Theor.	0.435	16.400	1.047	0.84	10.55

- Experimental performance of InGaP and InGaAs junctions in line with expectations
- But InGaNAs cells constantly limited cell performance (current)
- Interim InGaP / InGaNAs cell:

Growth ID	Jsc[mA/cm^2]	Voc[V]	Pmax[W]	F.F.	Eff.[%]
R7072	8.388	3.122	0.077	0.74	14.05

- In a next step 2 optimization options were tested:

  1. Lowering the thickness of the layer stack on top of the InGaNAs cell

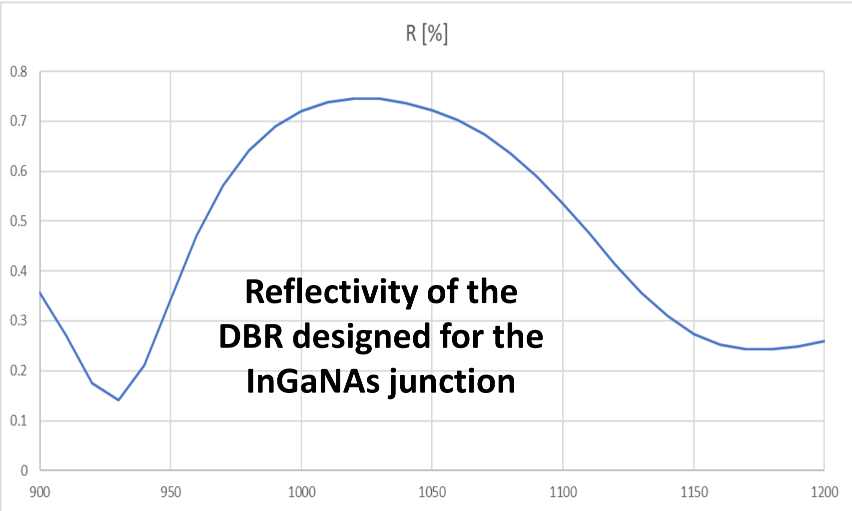
  2. Reducing the bandgap

- Full 4J cells:

Type	Jsc[mA/cm²]	Voc[V]	Pmax[W]	FF	Eff.[%]
Reduced MBE cap and MOCVD nucleation layer (A)	9.8	3.058	0.084	0.70	15.34
Reduced MBE cap and MOCVD nucleation layer (B)	9.1	3.042	0.072	0.65	13.15
Reduced InGaNAs Eg, MBE cap and MOCVD nucleation layer	**12.8**	2.968	0.107	0.71	19.63

- Therefore the focus was set on the InGaNAs development to reach a target current density of **16.1 mA/cm²** for enabling a feasible full 4J cell structure

- In a final step InGaNAs isotypes on passive Ge wafers with & without a **DBR** were tested:

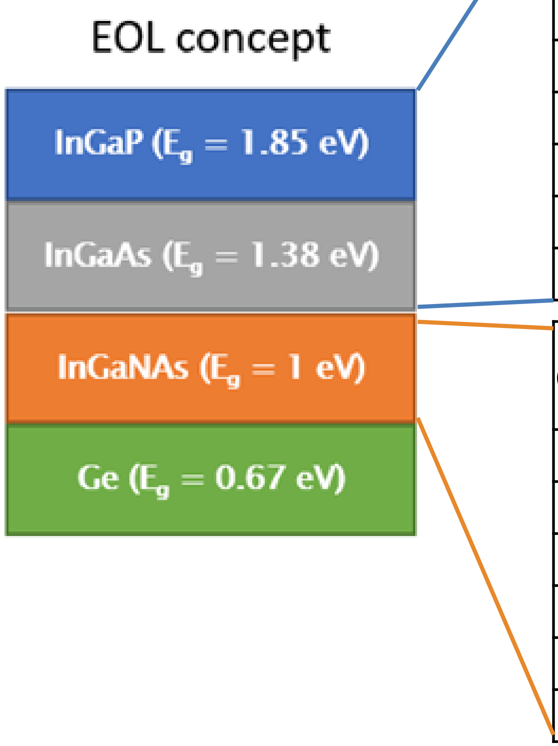


InGaNAs structure	DBR	MOCVD Run	Jsc [mA/cm^2]	Voc[V]	F.F.	Eff.[%]
As Ref. but thicker	Yes	#1	11.8	0.527	0.52	2.37
As Ref. but with narrower Eg	No	#1	14.8	0.409	0.63	2.81
As Ref. but thicker	No	#1	11.3	0.507	0.63	2.64
As Ref. but with narrower Eg	Yes	#1	11.4	0.481	0.51	2.02
As Ref. but with narrower Eg	Yes	#2	**15.9**	0.460	0.61	3.26
As Ref. but with narrower Eg	No	#2	13.9	0.399	0.63	2.57

- With a slightly reduced bandgap and a DBR optimized for the InGaNAs the target current density is almost achieved! (15.9 of 16.1 mA/cm^2 = 99%)

TBBs – 4J cells using InGaNAs cell technology

- Irradiation tests indicate that InGaNAs has higher degradation than



Cell	Status	Jsc [mA/cm²]	Voc[V]	FF	Eff.[%]
#A	BOL	16.41	2.297	0.84	22.5
#A	EOL	14.82	2.207	0.84	19.8
	RF	**0.903**	**0.961**	**0.99**	**0.878**
#B	BOL	16.41	2.296	0.83	22.5
#B	EOL	14.82	2.211	0.82	19.8
	RF	**0.903**	**0.963**	**0.99**	**0.882**

Cell	Status	Jsc [mA/cm²]	Voc[V]	FF	Eff.[%]
#C	BOL	15.78	0.408	0.57	2.67
#C	EOL	12.21	0.383	0.54	1.83
	RF	**0.778**	**0.939**	**0.95**	**0.685**
#D	BOL	15.82	0.454	0.58	3.08
#D	EOL	12.87	0.427	0.57	2.28
	RF	**0.810**	**0.941**	**0.98**	**0.740**

- Thus further development is needed to increase radiation tolerance of InGaNAs

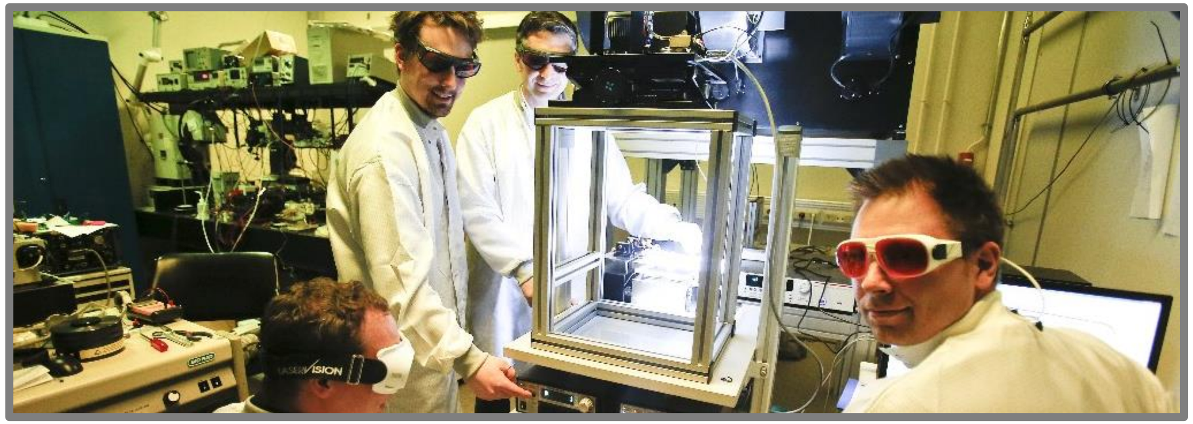
TBBs – InGaNAs cell technology (MBE growth)

ORC InGaNAs Solar Cell Activities in ESA IMPRO33

Arto Aho

Optoelectronics Research Centre, Tampere University, Finland
arto.aho@tuni.fi

Core competence

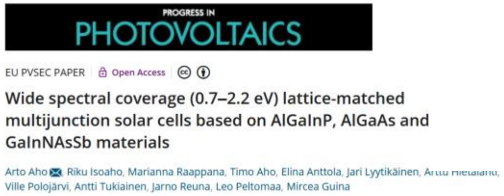


Fabrication approach: MBE-grown dilute nitride based Upright Lattice Matched (ULM) multi-junction solar cells (MJSC).

Key benefits: maximize the conversion efficiency by spectral matching using advanced materials

Best suited for space and concentrated photovoltaics

Highly Efficient use of materials, up to 75% savings, provide better volumetric efficiency, sustainability and higher effective payloads

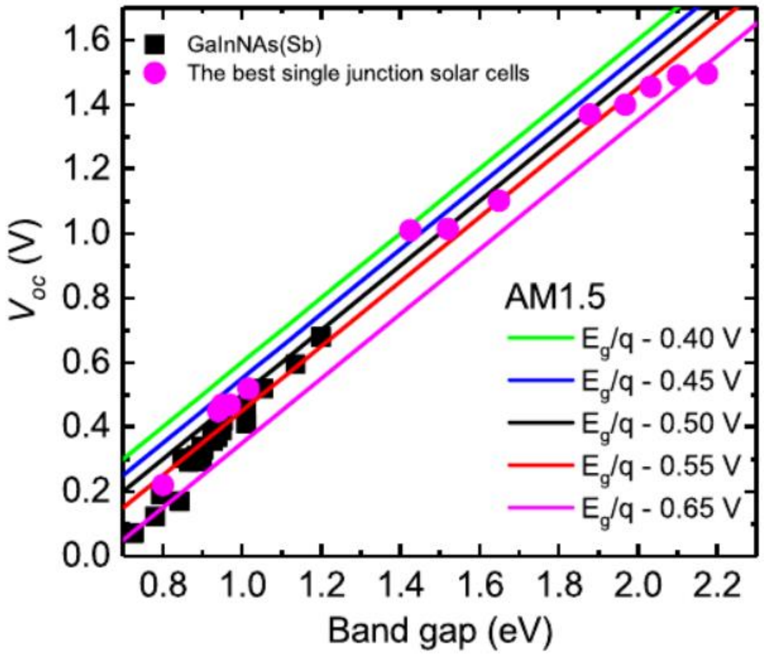


PROGRESS IN PHOTOVOLTAICS

EU PVSEC PAPER | Open Access

Wide spectral coverage (0.7–2.2 eV) lattice-matched multijunction solar cells based on AlGaInP, AlGaAs and GaInNAsSb materials

Arto Aho, Riku Isoaho, Marianna Raappana, Timo Aho, Elina Anttola, Jari Lyytikäinen, Ville Polojärvi, Antti Tukiainen, Jarno Reuna, Leo Peltomaa, Mircea Guina



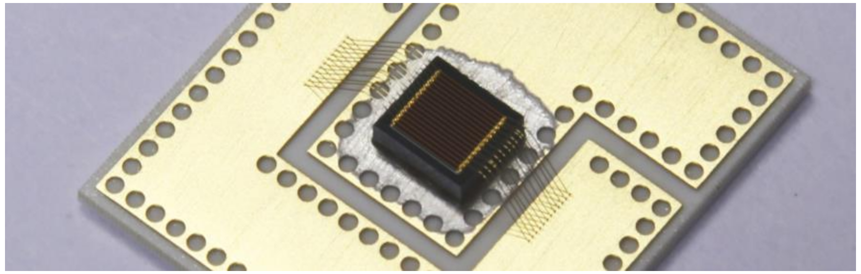
We have achieved:

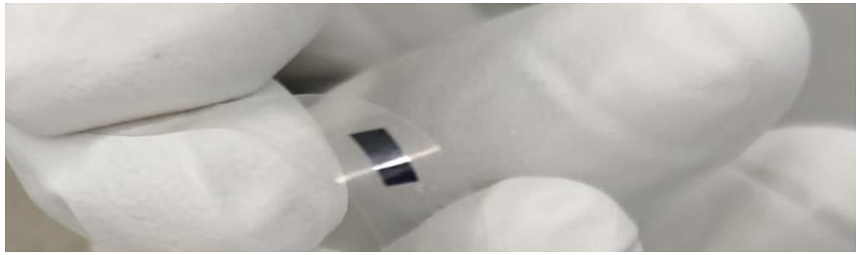
Space 3J > 30%

CPV 1000 suns, >40% achieved and >50% target

Key advantages

- **Proprietary** ULM MJSC MBE processes
- **Simple** wafer level processing
- **Sustainable** : minimal structural thickness (down to ¼ of current SoA)
- **Ultra-high** efficiency
- **Direct** exploitation to standard space systems to enhance the efficiency





Two development lines

ULM MJSCs 3J and 4J on GaAs

- **Simple** and thin design
- Flexible structures
- Simple wafer level fabrication

4J+ MJSCs on Ge

- **Thin** design and better **compatibility** for space
- **Scalable** MBE-MOCVD processes (in development)

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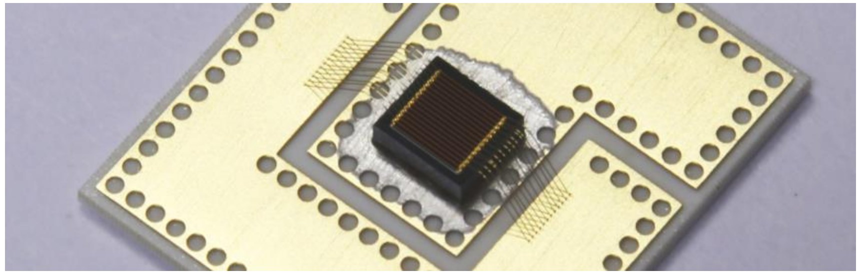

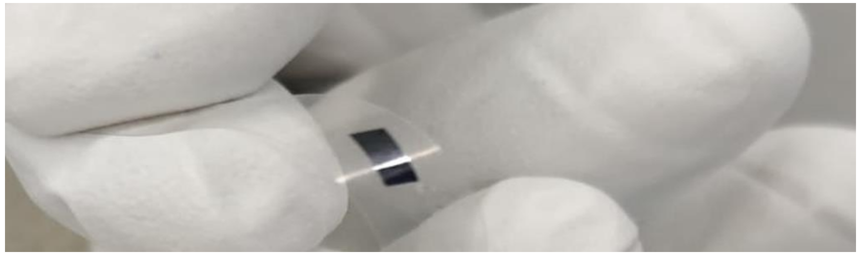

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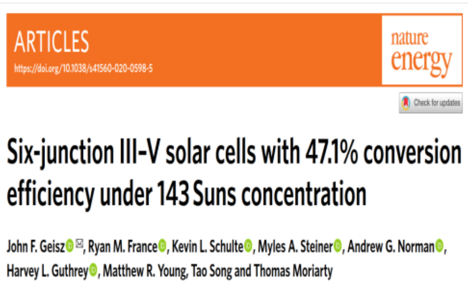

ARTICLES

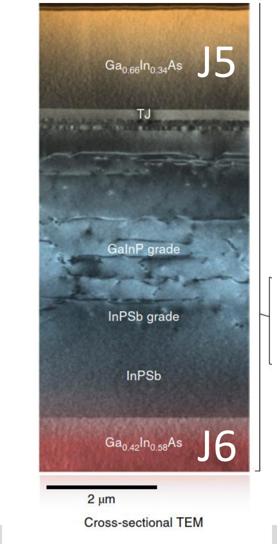
nature energy

https://doi.org/10.1038/s41560-020-0598-5

Check for updates

Six-junction III-V solar cells with 47.1% conversion efficiency under 143 Suns concentration

John F. Geisz, Ryan M. France, Kevin L. Schulte, Myles A. Steiner, Andrew G. Norman, Harvey L. Guthrey, Matthew R. Young, Tao Song and Thomas Moriarty



NREL 6J 47.1%
SC bot SCs

A. Aho et al., “Dilute nitride triple junction solar cells for space applications: Progress towards highest AM0 efficiency” Prog. Photovoltaics Res. Appl., 2018, https://doi.org/10.1002/pip.3011

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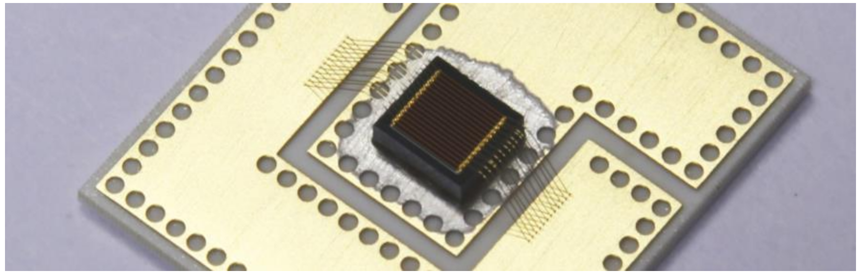

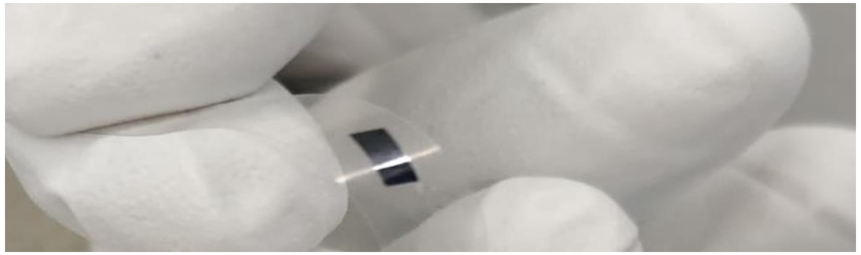

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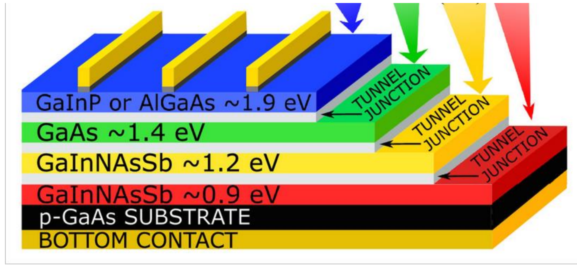

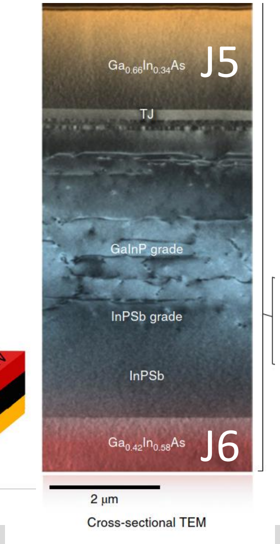

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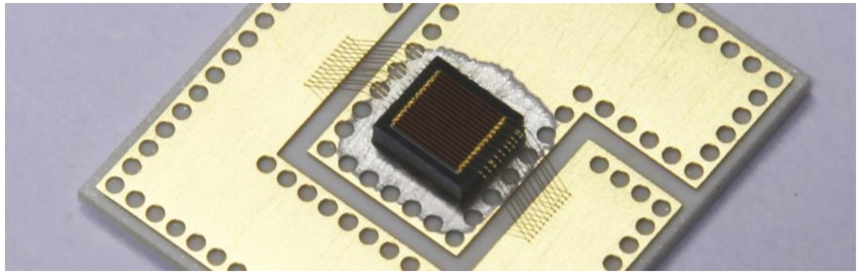

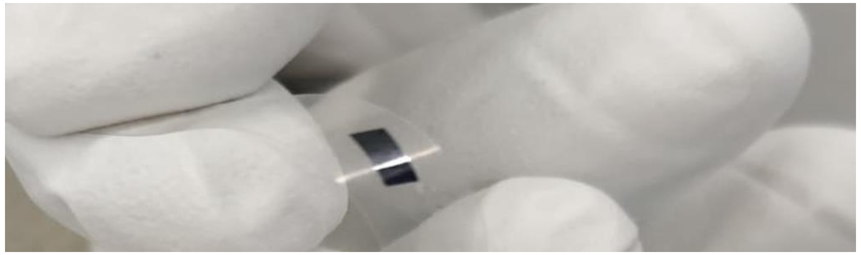

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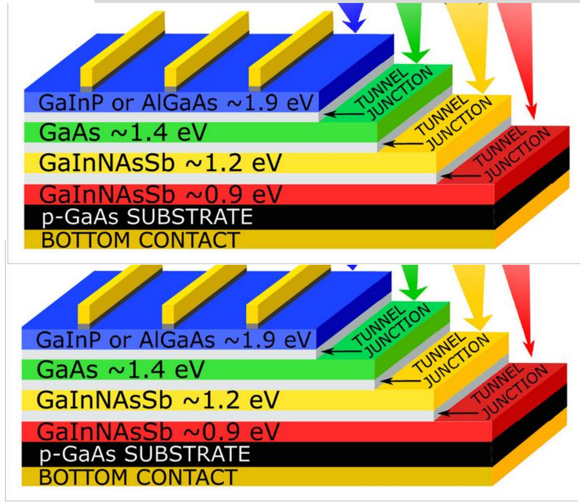

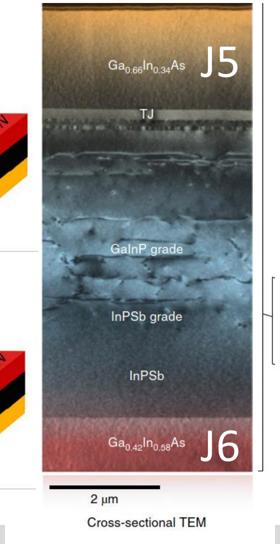

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IMPRO33 – ESA Project 2019 – 2022

esa

1. *Option 1: 4J on p-Ge*
    a. *Two step strategy – MBE + MOCVD (**Preferred**)*
        a. *PoC Nucleation studies by MBE*
    b. *Three step strategy –MOCVD + MBE + MOCVD (**Realistic approach in short term**)*

2. *Option 2: 4J on p-GaAs*

Option 1	Option 2
InGaP (E_g = 1.85 eV)	AlInGaP (E_g = 1.98 eV)
InGaAs (E_g = 1.38 eV)	AlGaAs (E_g = 1.71 eV)
InGaNAs (E_g = 1 eV)	GaAs (E_g = 1.4 eV)
Ge (E_g = 0.67 eV)	InGaNAs (E_g = 1 eV)

ORC + CESI

(MBE + MOCVD (Italy))

Our previous record is 30.8% for 3J

PROGRESS IN PHOTOVOLTAICS

RESEARCH ARTICLE | Full Access

Dilute nitride triple junction solar cells for space applications: Progress towards highest AM0 efficiency

Arto Aho, Riku Isoaho, Antti Tukiainen, Gabriele Gori, Roberta Campesato, Mircea Guina

First published: 10 April 2018 | https://doi.org/10.1002/pip.3011 | Citations: 1

Tampereen yliopisto
Tampere University

IMPRO33 – ESA Project 2019 – 2022

esa

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~~*2. Option 2: 4J on p-GaAs*~~ *(cancelled due to spare part issues)*

Option 1	~~Option 2~~
InGaP (E_g = 1.85 eV)	~~AlInGaP (E_g = 1.98 eV)~~
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ORC + CESI

(MBE + MOCVD (Italy))

Why MBE and/or MOCVD?

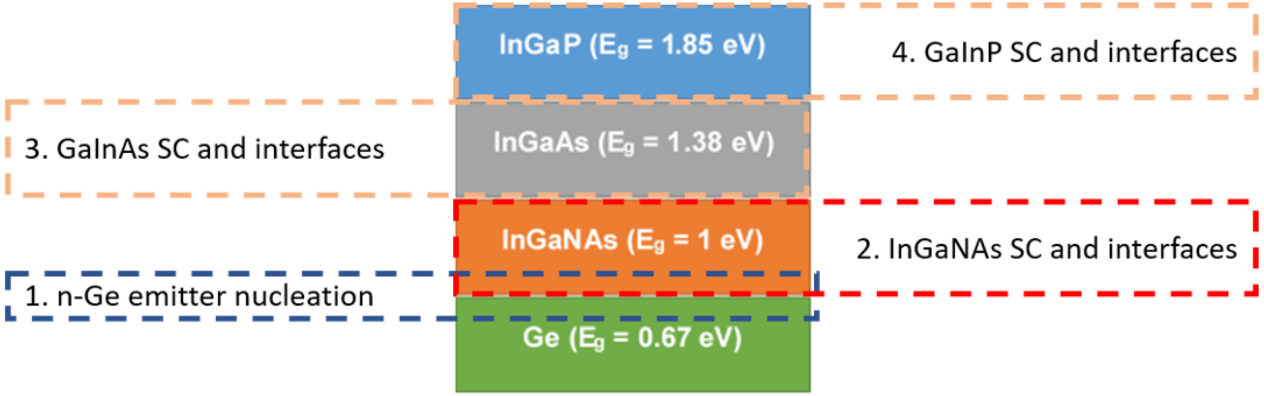
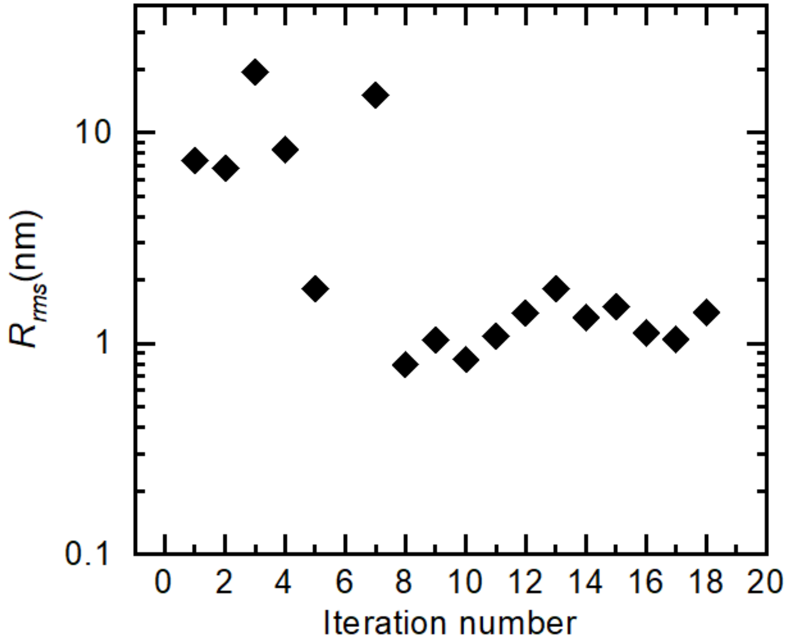


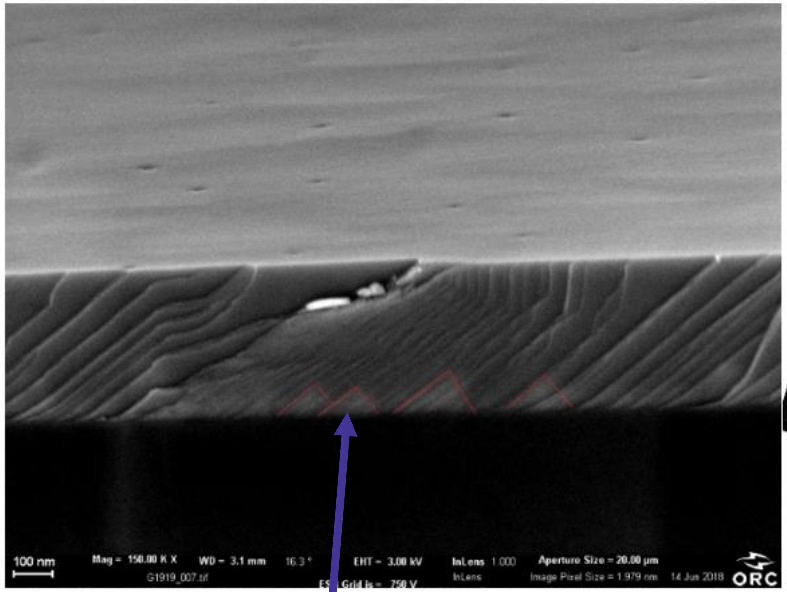
Fig. 2: *Basic principle of the combined MBE-MOCVD technique.*

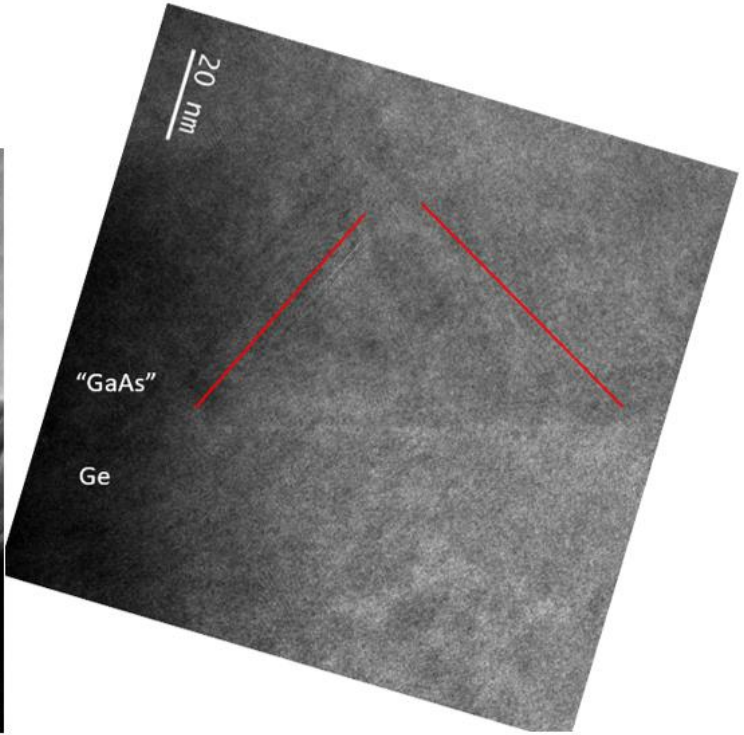
Table 1. *Performance comparison table for MOCVD and MBE.*

	Process maturity level	
Process step	**MOCVD**	**MBE**
1. n-Ge emitter nucleation (*Note: Needed only for the Concept 1*)	*Well established / industry standard*	***Novel**, some scientific reports are available, but best to our knowledge there is no functional III-V/Ge SC demonstrations.*
1. InGaNAs SC and interfaces	*Widely studied (NREL / Fraunhofer), but not applied due to process limitations and device quality. Expensive precursors and low J_{sc} values.*	*Fundamentally proven and formerly commercially applied for fully MBE grown 3J structures. High performance demonstrated with MBE-MOCVD grown GaInP/GaAs/InGaNAs (ORC + CESI)*
2. Ga(In)As SC and interfaces	*Well established / industry standard, high speed.*	*Well established (optional method)*
3. GaInP SC and interfaces	*Well established / industry standard*	*Well established (optional method)*

Direct III-V nucleation on p-Ge by MBE







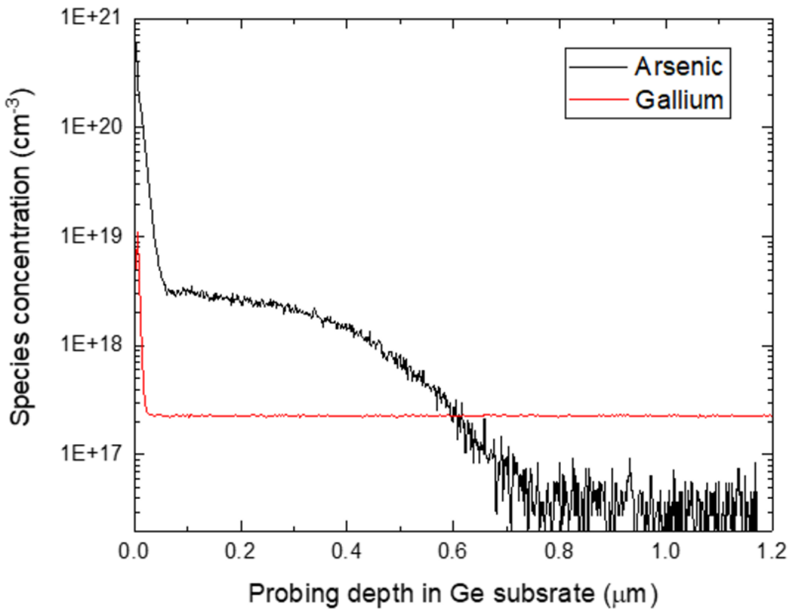
APD ”pyramids” visible for the samples that were unoptimized. For the optimized buffers, SEM and TEM investigations showed similar III-V/Ge interface characteristics for MBE and MOCVD references.

”We have planned to conduct more measurement, such as cathode luminescence for analysis of the APDs.”

Tampereen yliopisto
Tampere University

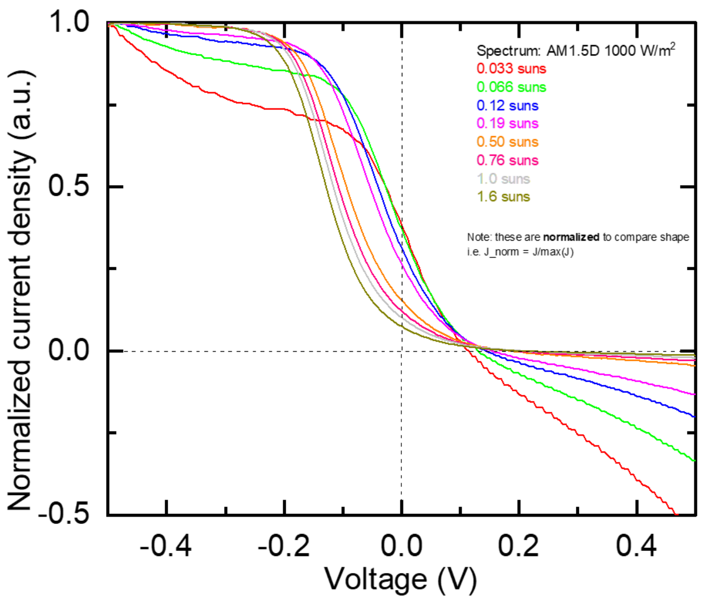
MBE nucleation: Junction profile and PV characteristics

SIMS



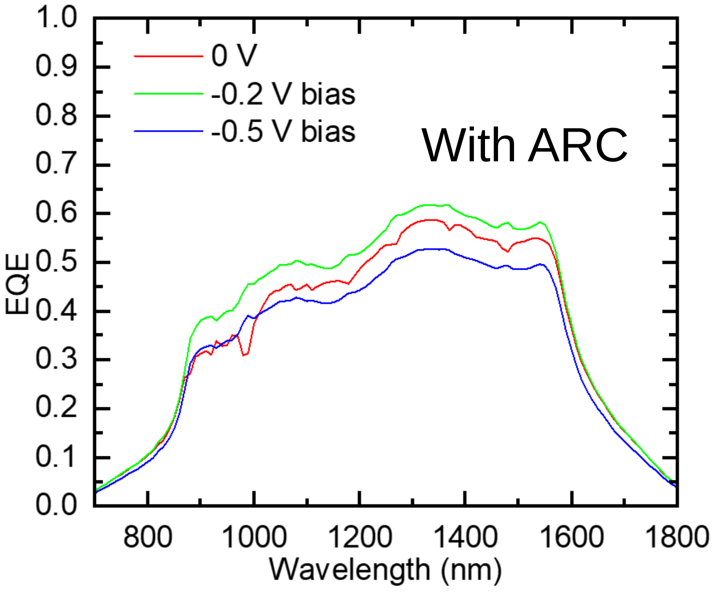
"*Significant diffusion of As meas*"
Further profile **optimization** needed

IV



"Photocurrent and voltage!"
But **only** ~60 mV and J_{sc} of 7 mA/cm^2

EQE



"***Up to 50% EQE*** (17.9 mA/cm^2 @ AM0)"
Good response only with small signal

Diffused Ge junction by MBE

Summary: ***It works, but it is not practically usable yet*****.**

Tampereen yliopisto
Tampere University

Concept 1: GaInP/InGaAs/InGaNAs/Ge 4Js

IMPRO33 PoC GaInP/InGaAs/InGaNAs/Ge 4J

EQE and analysis

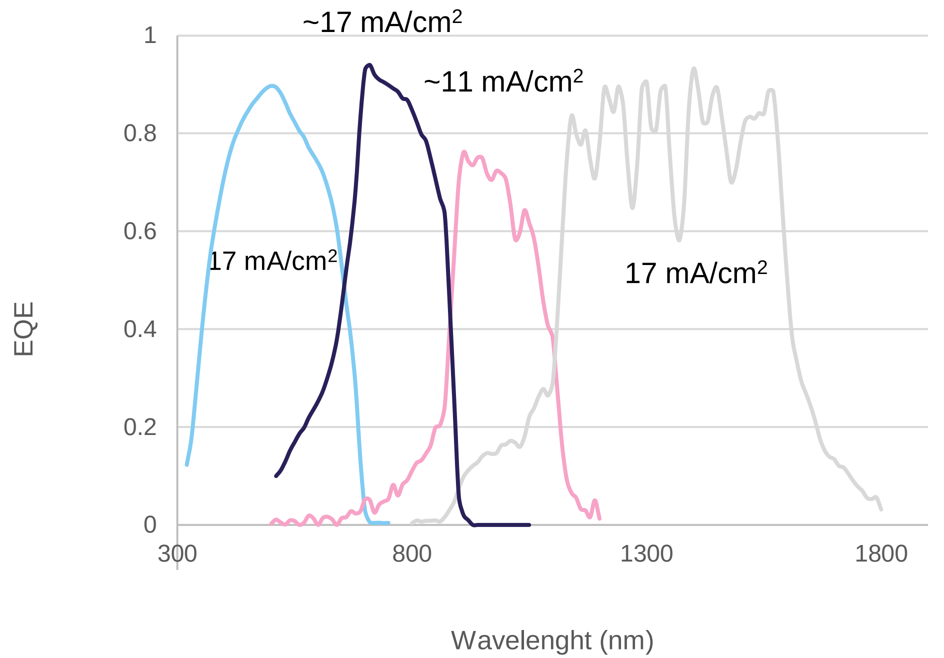
→ EQE/IQE measurements for GaInP, InGaNAs and Ge junctions. Ga(In)As biasing is challenging → EQE modeled for InGaAs.

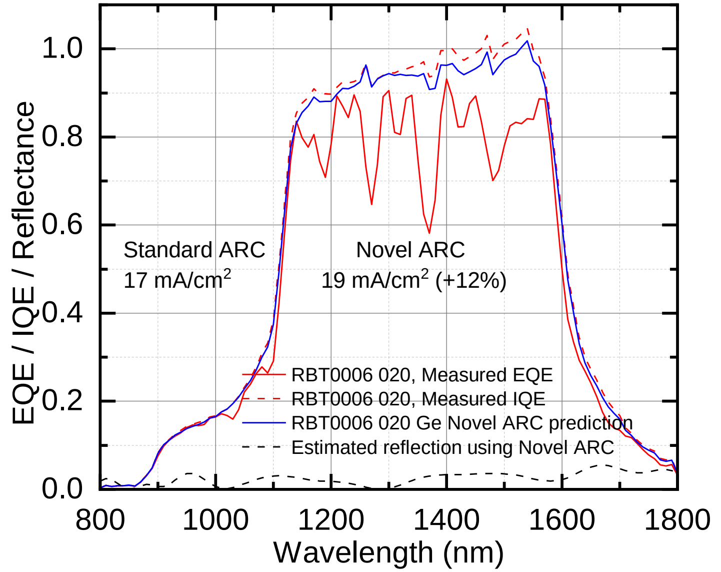
→J_{sc}(EQE) from **11** to **14** mA/cm^2 by InGaNAs quality optimization (Simulations). *Photons are absorbed but are not collected*.

→ ARC refleflection losses @ IR are significant: InGaNAs (0.5 mA/cm2) and Ge (3 mA/cm^2)

→ Maximize InGaNAs J_{sc}

→ Optimal InGaNAs, optimal Eg and thicknesses
→ Novel ARC for 4J might provide significantly better efficiencies
Novel ARC has been PoC tested on TAU 4J (MBE grown), significant J_{sc} boost for long IR SCs





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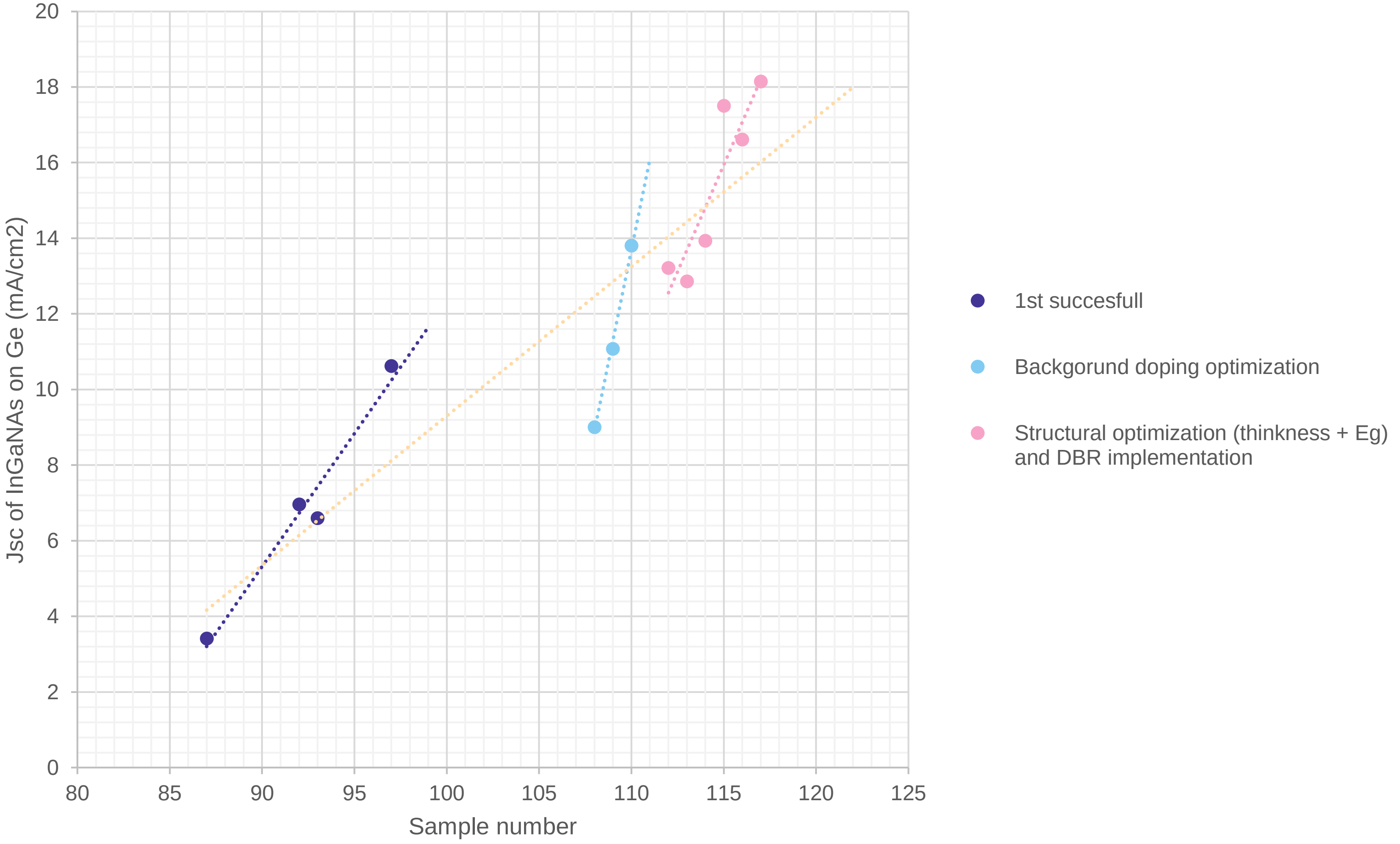
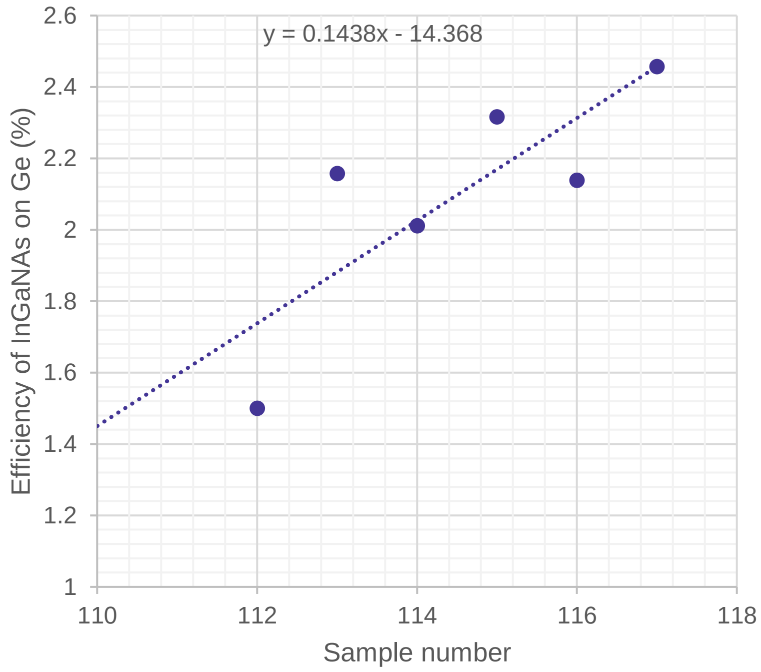
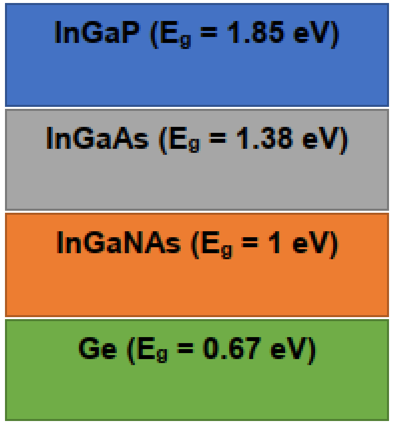
Tampere University

J_{sc} evolution during 2021(Q3/Q4) and 2022 (Q1/Q2) for the 4J on p-Ge concept



Note: J_{sc} data from CESI solar simulator measurements, assumes perfect ARC.





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IQE for the growht optimized SCs

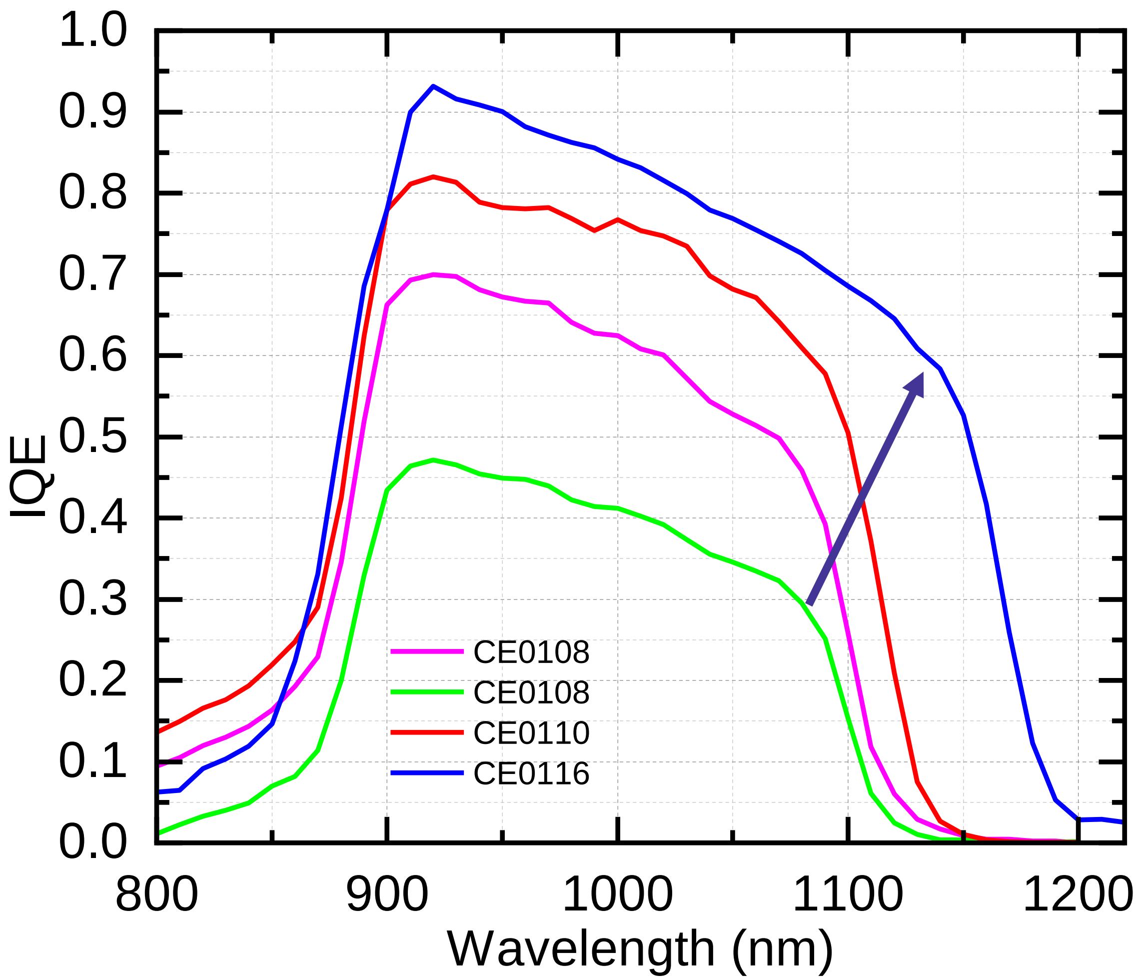
<u>**The (successful) MBE Growth iterations**</u>

Background doping

- By optimizing the background doping, IQE max varies from 45 to 90%

Further *E_g* tuning down to 1.03 eV:

- Lessons were learned from the optimization and further reduction of Eg was made by 60 meV. ***E_g*** is now 1.03 eV and the performance is good for an InGaNAs SC.



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The Last iterations w/ structural changes: more E_g tuning and DBR incoporation

E_g (1.09 eV) :

- The effect of thicker junction + 0.5 mA/cm^2
- **DBR** effect: +0.7 mA/cm^2
  - Est. total enhancement pot recorded: 1.2 mA/cm^2

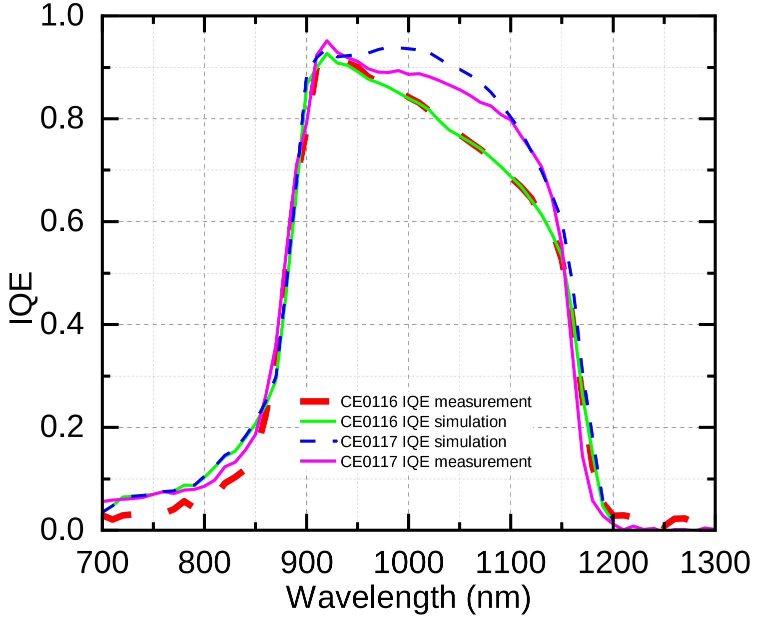
More E_g tuning (1.03 eV):

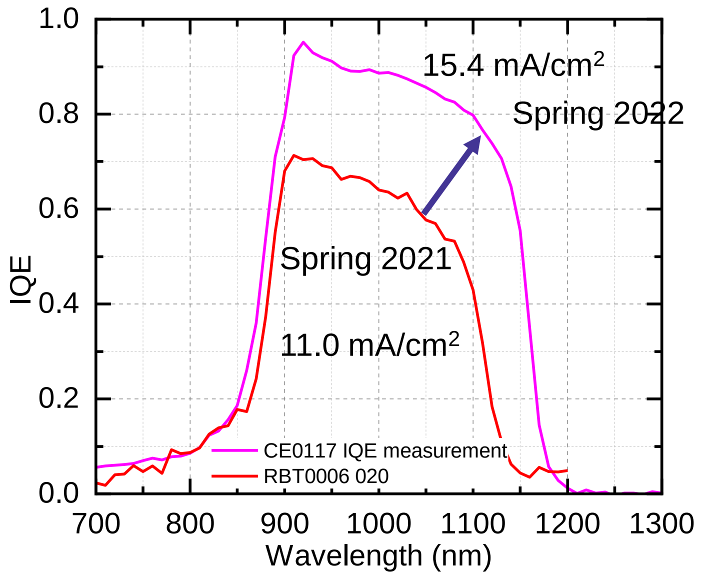
- **Minus 60 meV Eg**: +3.7 mA/cm^2
- **Minus 60 meV Eg** + DBR: +3.7+0.7 mA/cm^2

CE0116: Eg = 1.03 eV, w/o DBR: 14.7 mA/cm^2
CE0117: Eg = 1.03 eV, with DBR: 15.4 mA/cm^2
-11.0 mA/cm2+3.7 mA/cm2+0.7 mA/cm2 = 15.4 mA/cm2

Simulation for CE0117 structure: 16.0 mA/cm2

ICE ~100%





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Tampere University

The Last iterations, more E_g tuning and DBR in

E_g (1.09 eV) :

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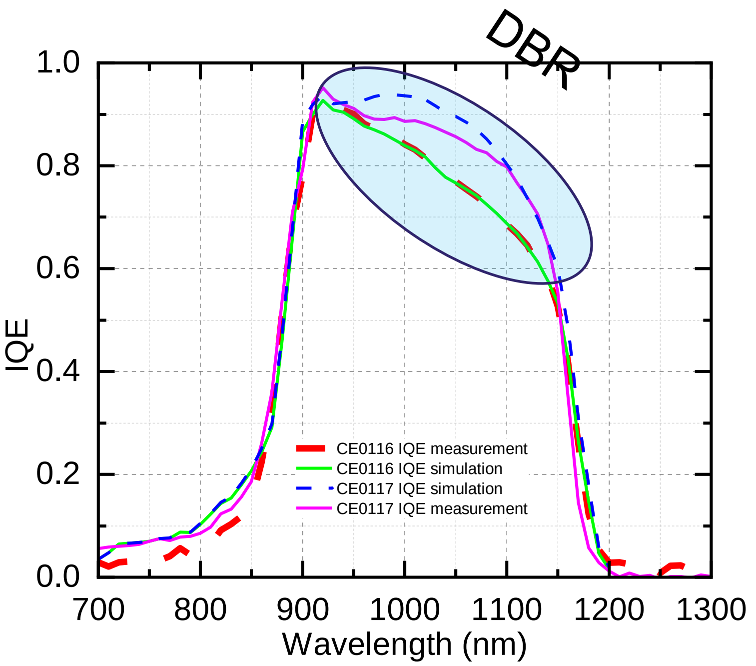
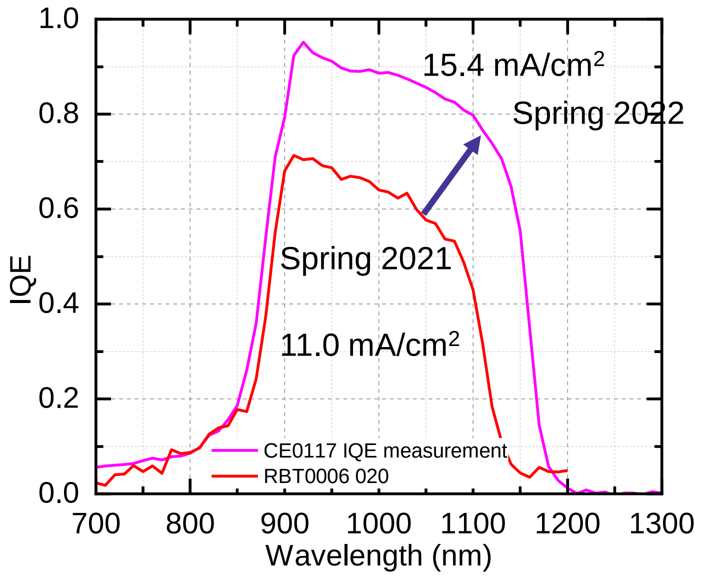


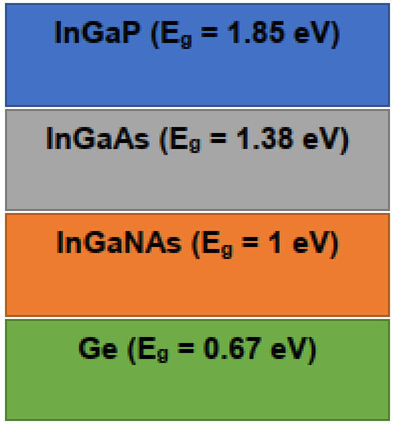


Summary

LM InGaNAs 4J MBE-MOCVD architectures were studied

- ✓ PoC diffused Ge junctions demonstrated by MBE
- ✓ PoC GaInP/InGaAs/InGaNAs/Ge were fabricated
- ✓ Over 90% IQE achieved, similar than for 3J concept on GaAs
- ✓ Further iterations would result in better BOL and EOL
- ✓ Based on these observations,we claim that high current (/ efficiency) **GaInP/InGaAs/InGaNAs/Ge** can be made using MBE-MOCVD

ORC + CESI



MBE + MOCVD

Thank you!

projects.tuni.fi/ametist
Arto Aho @ Google Scholar
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European Research Council
Established by the European Commission

Innovative Ge substrates by umicore

Wafer types and 3J solar cells made at CESI, ISE & AZUR

AZUR SPACE
ENABLING TECHNOLOGIES

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- Three different types of innovative Ge substrates have been provided by Umicore to CESI, AZUR and ISE

  → Type1: 'Basic' / Type2: 'Mid-range' / Type3: 'High-range'

- All partners applied MOVPE of 3J-LM (SoA) space cell structures on them

- Finally std. space solar cell manufacturing was performed and AM0 measurements were performed at each partner directly comparing

  Inno. Ge substrates vs. Ref. Ge substrates

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Results at AZUR SPACE ('3G30'):

- All types after epitaxy optically show significant issues (rough, wavy)
- 'Basic' type → 100% outage (eta: ~20%)
- On 'Mid-range' wafers up to **28.3%** eff. is reached (approx. 1.5 – 3.5%$_{abs.}$ less than ref. & high deviations)
- On 'High-range' wafers good reproducibility achieved, but on relatively low level ($\eta_{avg.}$: ~26%; approx. 3%$_{abs.}$ less than for Ref.)

Results at CESI ('CTJ30'):

- All types after epitaxy optically show significant optical issues (rough, wavy)
- Basic type shows significant losses in V_{oc}, FF and efficiency → outage (also)
- But 'Mid-range' & 'High-range' wafers achieve highly promising electrical results;
  → 'Mid-range' : approx. **-0.7%$_{rel.}$** / 'High-range': approx. **-0.3%$_{rel.}$**

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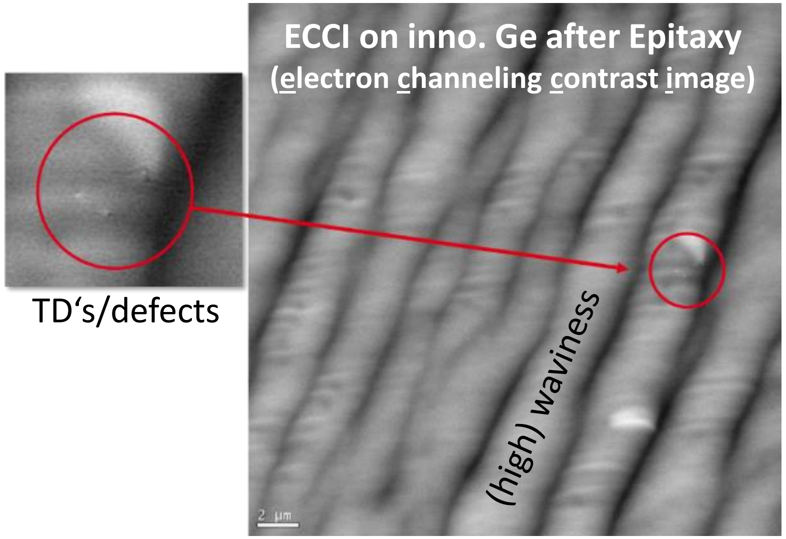
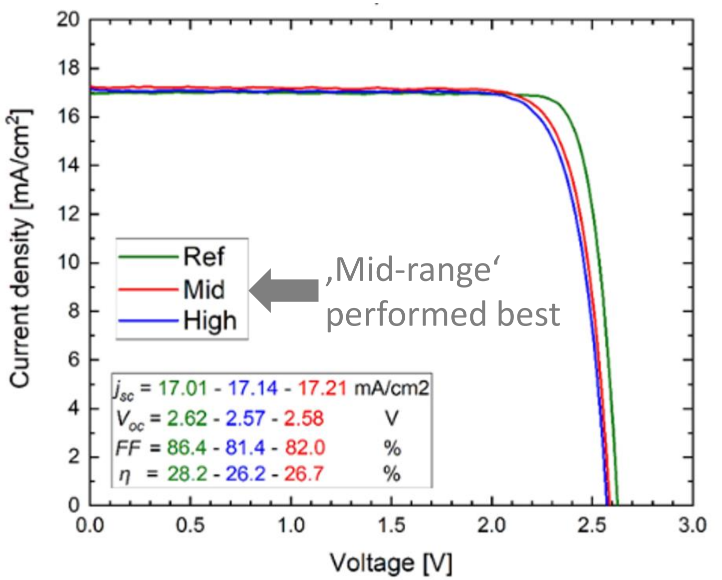
Results at FhG ISE (DHS + 3J structures):

- RMS measurements locally (2x2µm²) for all types <1nm and similar!; On 10x10µm² area:
  4 .. 2 nm -> 'Basic' to 'High-range'; Ref. <1nm
- Cathodoluminescence on DHS shows **TDD** for ‚Basic' type is clearly increased, but for other types <1E5 cm^{-2} and almost on same level as reference (<4.5E4 cm^{-2})
- ECCI confirms 'waviness' but low defect rates on surface after epi on inno. Ge substrates
- On 'Mid-range' η=26.7% reached ($\Delta\eta_{Ref.}$: -1.5%$_{abs.}$)





Summary and Conclusions

AM0 efficiencies

Low-weight & mech. flexibility

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AM0 solar cell efficiencies:

- Max. AM0 BOL efficiency achieved by 4J-UMM cell (**32.4%**)
- 4J-IMM developed and **30.9%** achieved (potential of approx. 33.8%)

  → Next step towards 5J-IMM in reach (next major development step)
- InGaNAs after issues on ‚good level again‘; unfortunately no optimization of sub-cells for full 4J structure was possible; but $J_{SC,InGaNAs}$ target almost reached (**15.9 mA/cm²**)

Specific cell mass/area:

- Extremely low area-related mass achieved by IMM (**14.1 mg/cm²**) → >2.7 kW/kg
- Target also achieved with thinned 3G30 bare cell (**19.1 mg/cm²**)
- Thin & mech. Flexible SCA‘s manufactured successfully (**R_{bend} = 50 mm**)

Innovative Ge substrates

- Highly promising results for 3J-LM space cells achieved (especially at CESI)

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Thanks for your kind attention!

... and stay healthy!