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

Impro-33

Executive Summary Report

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1 Introduction

In order to satisfy different demands in the highly competitive space solar cell market, novel solar cell concepts are needed. To date a number of concepts is in development worldwide ranging from single-junction Si cells to sophisticated 4J or even up to 6J tandem cell structures based on III/V semiconductor compounds. However, it is not possible yet to reasonably predict what concept shall be prioritised for commercial products and for which space application (LEO, MEO, GEO). Consequently, in the framework of the IMPRO-33 development activity a several solar cell concepts and corresponding technology building blocks that can be versatile applied were pursued. As a result, the strengths and weaknesses of the different concepts could be assessed more accurately and the findings provide a sound basis for developing future cell products as well as selecting priorities for following development activities. Table 1-1 summarizes the cell concepts addressed in the project and their main purpose/targeted key performance factors.

Table 1-1: Summary of solar cell concepts and technology building blocks addressed in Impro-33

Solar cell concept	Main purpose / target market	Comments
UMM-4J adopted for BOL conditions	Ultra-high-efficiency BOL cell with up to 34%; → special LEO/MEO missions; potentially also HAPS market; need for high power and limited area for PV	Due to the higher V_{OC} and lower I_{SC} further practical advantages regarding the power management are expected.
Next generation UMM EOL cell (only buffer development addressed here)	Ultra-high-efficiency EOL cell with up to 33% at EOL (1E15 e^-/cm²; 1 MeV); → EOR and other missions with need for ultra-high radiation tolerance	Development limited to buffer & one sub-cell, as full UMM tandem cell structure too complex for project time frame/budget
Ultra-thin bare solar cells	Generic; all applications with need for higher power/mass ratio and mechanical flexibility	To take advantage of this cells also a novel / thin encapsulation is needed as standard cover glass limits mass and mechanical flexibility
Thin & flexible SCAs	Generic; all applications with need for higher power/mass ratio and mech. flexibility	Conservative SCA's using standard materials only & still providing sufficient mech. flexibility for most existing flexible PV module concepts
IMM-4J BOL cell	Ultra-high-efficiency BOL and low-weight cell; in particular interesting for LEO/HAPS missions with need for max. power/mass ratios	IMM also allows a substrate re-use option for epitaxy, and therefore can become highly cost-effective in the future
InGaNAs-4J BOL cell	Ultra-high-efficiency BOL cell with up to 35%; → special LEO/MEO missions; potentially also HAPS market; need for high power and limited area for PV	Sub-cell based InGaNAs material cell allows an almost ideal band gap selection for a 4J cell without the need of a metamorphic buffer
InGaNAs-4J EOL cell	Ultra-high-efficiency EOL cell with up to 33% at EOL (1E15 e^-/cm²; 1 MeV); → EOR and other missions with need for ultra-high radiation tolerance	An InGaNAs sub-cell allows an almost ideal band gap selection for a 4J cell without the need of a metamorphic buffer
Innovative Germanium substrates	Generic; all markets with need for lower costs	Optimized wafer cost-effectiveness for growth of space solar cells

2 Project work logic

The Impro-33 project was split in five tasks as schematically shown in figure 2-1. Within each task the different cell concepts and technology building blocks were developed in parallel.

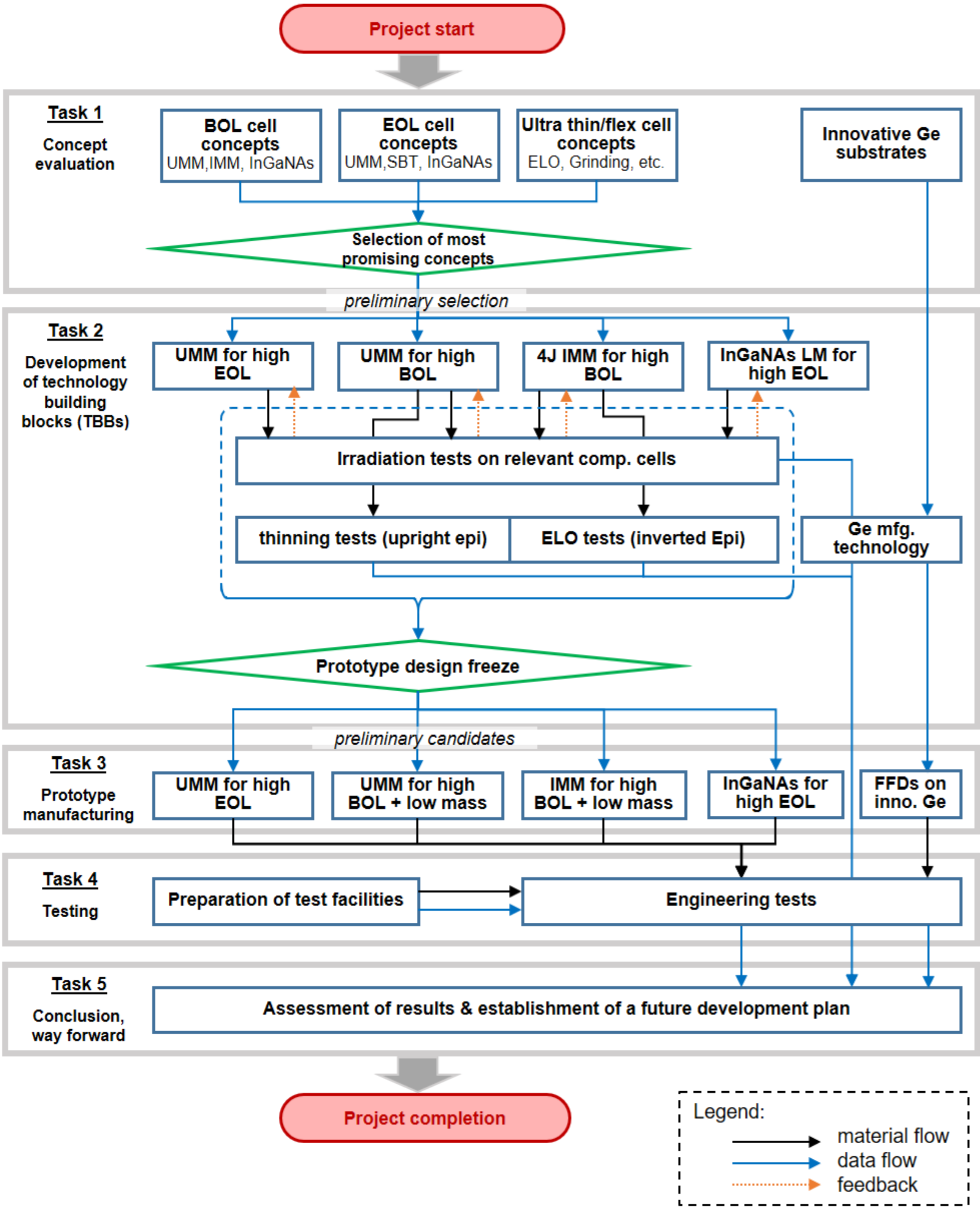

Figure 2-1: Development work logic and interaction between with the five defined project tasks

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3 Main Achievements

3.1 Upright metamorphic (UMM) cell concepts

In the framework of Impro-33 we pursued two topics important to address improvements of BOL and EOL efficiency of UMM solar cells. On the one hand, we developed a novel metamorphic buffer structure with high Indium content that is required for a particular cell architecture for ultra-high EOL performance potential of above 30%. This development was dedicated to development of the buffer structure and corresponding InGaAs single-junction cell to evaluate the quality of buffer layer. This development is considered as fully successful. Final single-junction cells with the adopted lattice constant and band structure showed up high quantum efficiency and reached the open circuit voltage expected from simulations. In the table 3-1, the achieved remaining factors of the isotypes made on the novel buffer is given and compared to 1J InGaAs cells (isoypes) from the 4G32 the cell structure used as reference. The achieved results confirm that the quality of the novel buffer material is similar to this of the 4G32 InGaAs reference isotypes. Furthermore, the remaining factor (RF) values after 1E15cm^{-2} 1 MeV electron irradiation is even higher for the cells on the new buffer. This is an indicator for a general higher irradiation tolerance of the InGaAs cell material with higher Indium content.
Further development focus was related to improvement of the BOL cell efficiency of UMM cells. This topic is considered as highly relevant for space market in the coming years. As the baseline we used our EOL optimized 4J-UMM cell architecture 4G32-Advanced and investigated different option to optimize this cell for BOL conditions. In the final campaign two cell modifications comprising a current-matching structure ('Var-1') as well as a band-gap tuned structure ('Var-2') were tested. Both of these two modifications exhibited the same BOL improvement and achieved ≥2%rel. higher efficiency than the 4G32 state-of-the-art technology (AM0, 1367 W/m², 25°C) shown in figure 3-1.

	Reference isotype (4G32)	Isotype on new buffer (high In-content)
RF [%]	**80.1**	**82.4**

Table 3-1: Achieved remaining factors of isotype cells on Ref. and novel buffer with increased In content

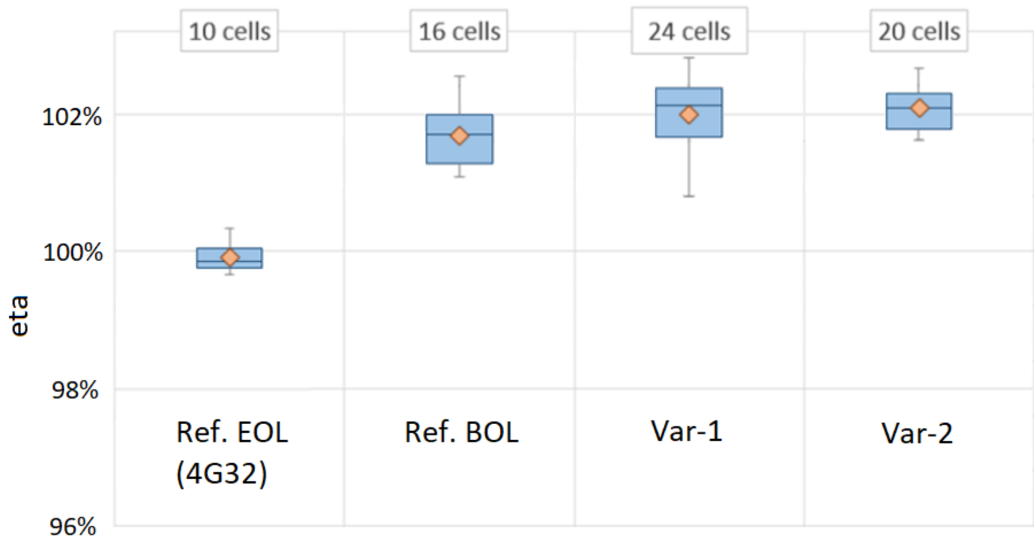
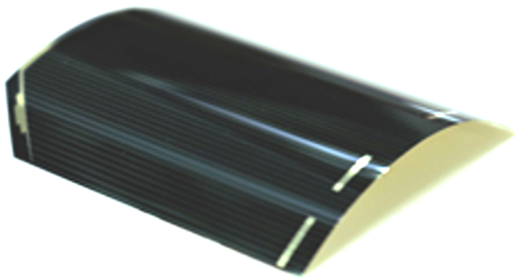


Fig. 3-1: AM0 (1367 W/m², 25°C) BOL cell efficiencies demonstrated for references ('Ref EOL'), an interim BOL variant ('Ref BOL') and the two structure modifications ('Var-1' and 'Var-2')

3.2 Ultra-thin, low-weight and flexible bare solar cells and SCA's

Within Impro33 activity, besides the efficiency targets also the reduction of the bare cell and SCA weight was pursued. The target value for the area-related mass of 20 mg/cm² on bare cell level was successfully achieved. Compared to a standard and non-thinned germanium based 3J cell like 3G30 with a thickness of approx. 150 µm, this corresponds to an improvement by a factor >4. To reach this, most of the germanium substrate was removed (>70%). This thinning approach is compatible with the Ge recycling process already established at AZUR. Therefore, the major milestone for very promising technology building block was achieved. In figure 3-2, a photograph of a fabricated ultra-thin cell is shown (left) and electrical performance of 8 selected sample cells is given (right). Considering the demonstrated AM0 efficiency of 29.4% and the cell mass of 20 mg/cm², the cells achieve a mass-related power metric of approx. 2 kW/kg.



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

Fig. 3-2: Image of an ultra-thin bare solar cell (left) and LIV (BOL) data of 8 selected cells (right)

In addition, thin cell samples were processed to solar cell assemblies (SCA's). For this, dedicated cover glasses were attached to the cells in order to achieve maximal mechanical flexibility and allowing small bending radii respectively. The smallest bending radius tested was at R = 50 mm. We succeeded in manufacturing a number of SCA samples with full 4x8 cm^2 standard format, which passed bending tests without damage. This was examined by electroluminescence (EL) characterization before and after bending tests. In figure 3-3, images illustrating the bending tests are shown.

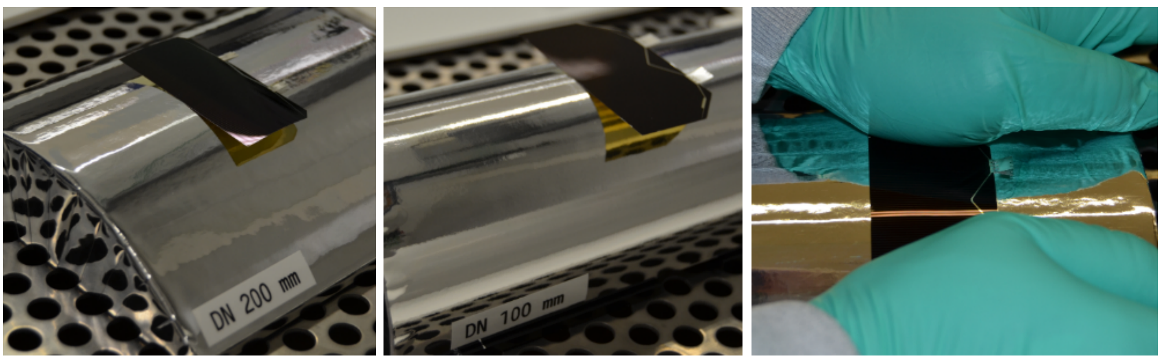


Figure 3-3: Photographs of bending tests (note: on the tools the diameter instead of the radius is displayed – so the 100 mm tool in the middle image corresponds to a radius of 50 mm);

3.3 IMM-4J space solar cells

In Impro-33 the development of a 4J-IMM solar cell concept was pursued, which is considered a mandatory interim step towards a potential 5J-IMM cell structure having a BOL AM0 efficiency potential of up to almost 36%. Figure 3-4 outlines the pathway towards the 5J concept and already achieved IMM solar cell efficiencies. And as currently US companies are clearly leading in respect to the IMM technology, we see the need for action on catching up on this important development. Referring to this, within the framework of Impro-33 major steps could be achieved.

The 4J IMM development was divided into epitaxial development at Fraunhofer ISE and solar cell processing sequence at tf2 devices. Analysis on the epitaxial structure comprising LIV and QE data shows that J2 is limiting the total cell current and responsible for the reduced current of ~0.3 mA/cm². This, in combination with reduced FF, are the main losses limited the achieved 'Gen II' IMM-4J cell to 30.9% compared to the simulated 33.8% efficiency potential. In figure 3-5, the LIV curves of the achieved 4J-IMM and the simulated potential are plotted. We consider this a significant step forward in terms of the IMM development in Europe. Successful improvement of the J2, will also enable a first potential feasible IMM cell product comes within reach. However, to exceed the 34% BOL efficiency level, a high band-gap top junction is needed, which will require further development work.

In the field IMM cell processing also considerable improvements were reached within the Impro-33 project. One major topic was the development of an appropriate mesa etching process sequence considering the different III/V semiconductor materials included in the 4J-IMM stack. Here, a well working solution was found and evaluated by successful manufacturing a series of 20 cm² demonstrator IMM cells (see fig. 3-6).

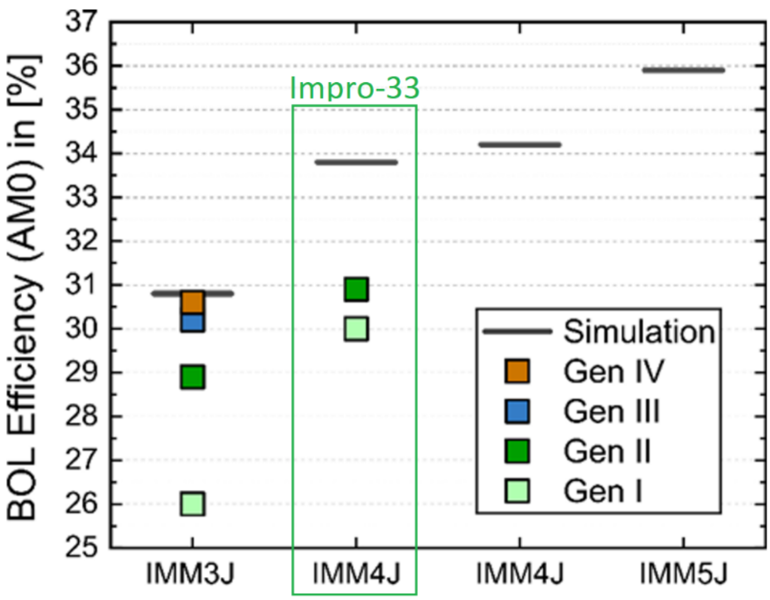


Figure 3-4: Efficiency potentials according to device simulations (AM0) for IMM-3J up to IMM-5J cell concepts. Note: the 2nd IMM4J cell simulated uses a higher band-gap top-cell (>2 eV); the same applies for the IMM5J

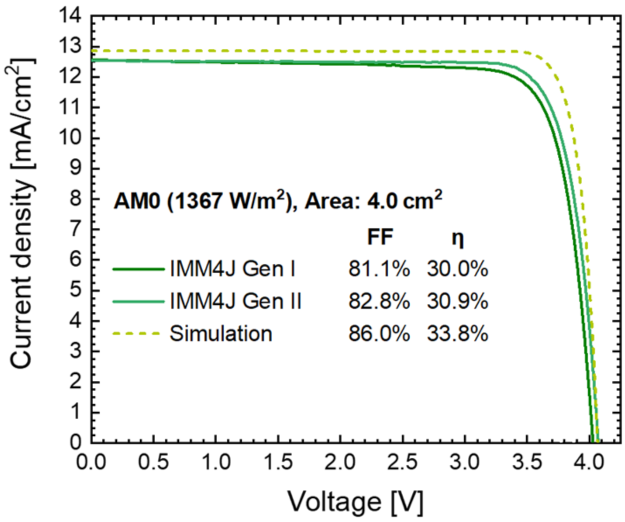


Figure 3-5: Light I-V of the best 4 cm² devices in comparison to the simulated BOL target. While the V_{OC} is already close to the target, there is still a current limitation due to the J2 and a significant FF deviation that most probably is caused by a so far not identified unexpected series resistance.

Figure 3-6: Example of a 20 cm² ultra-thin IMM-4J space solar cell.

In addition, several technology building blocks regarding the rear side processing were developed. One point was the substitution of the standard metal by an alternative metal, which by simulations was expected to achieve better reflectivity and thus an improvement of the QE in the long wave length region. However, contrary to the simulations no significant improvement is observed with the newly tested metal, neither in reflectivity measurements, IV measurement nor EQE measurements. Therefore, this development is put on hold. Another method to improve the rear side reflection and also the rear surface passivation, is the incorporation of a dielectric layer between the semiconductor and rear side metal. This was tested on 1J-IMM test cells and a V_{OC} improvement of +15 mV (average) was reached. Also, the average J_{SC} is slightly increased - this effect is expected stronger for thinner (sub-)cells. However, the average FF of the cells was slightly reduced (~1.3%$_{abs}$). Therefore, further research is needed on this topic.

Finally, irradiation tests with doses of 1E14cm^{-2} and 2.5E14cm^{-2} were performed and annealing according to ECSS was performed. In table 3-1 the achieved BOL and EOL efficiency, mass specific power and areal mass density values of selected 4J-IMM samples are summarized. In terms of areal mass density, the targeted performance is clearly met, even greatly exceeded and specific power also for 2.5E14 is over 2.5 kW/kg. The BOL efficiency requirement also is met, whereas the hero 4J-IMM cell reached an almost 1%$_{abs.}$ higher value (30.9%) than the samples shown in table 3-2.

Table 3-2: Performance metrics of the ultra-thin 4J-IMM4J cells at the end of the Impro-33 project.

IMM4J cell		η (%) (designated area)	specific power (W/g)	areal mass density (mg/cm^2)
Target performance (BOL)		>35.0		<20.0
Required performance (BOL)		>30.0		<50.0
4J-IMM cell-A	C4989 (BOL)	√ 30.0	2.50	√ 16.4
4J-IMM cell-B	C4989 (BOL)	√ 30.0	2.61	√ 15.7
4J-IMM cell-C	C4991 (EOL)	28.1	2.73	√ 14.1
4J-IMM cell-D	C4991 (EOL)	28.6	2.67	√ 14.6

For sure there is still room for improvement, but it should be noted that the 4J-IMM structure developed as part of the Impro-33 project is mainly intended as an intermediate step towards the goal of achieving a future IMM cell structure with BOL efficiencies up to 35%. The corresponding realistic potential efficiency of the presented Impro-33 4J-IMM design is calculated to be 32.6%. Thus, approx. 95% of its potential is achieved here as part of this activity, which we consider a major step forward on the IMM technology development in Europe.

3.4 InGaNAs 4J space solar cells

Initially the development of two tandem solar cell concepts using an InGaNAs sub-cell were planned in the Impro-33 program. One concept aiming for a maximal BOL efficiency, while the second concept targeted on an optimized EOL performance (@1E15). The schematic built-up of both concepts is shown in figure 3-9, in table 3-3 the calculated BOL and EOL cell performance parameters and estimated efficiency potentials are summarized.

Table 3-3: BOL and EOL cell parameters and estimated efficiency potentials of the BOL and EOL 4J LM

	EOL concept (without Ge sub-cell)		**EOL concept** (with Ge sub-cell)	
	BOL	**EOL**	**BOL**	**EOL**
J_{SC} (mA/cm^2)	12.4	11.6	16.1	15.7
V_{OC} (V)	4.464	4.160	3.379	3.367
FF	0.87	0.86	0.87	0.83
eta (AM0, 25°C)	***35.3%***	30.2%	34.6%	***31.9%***

However, to date it seems almost impossible to achieve sufficient InGaNAs material quality by an industrial feasible MOVPE process to incorporate it in a full tandem solar cell structure. Therefore, the InGaNAs material for development purposes in most cases is grown by a MBE process separately, which also applies for the developments within the Impro-33 program whereas the MBE epitaxy was performed at Tampere University (TAU) and MOVPE at CESI. In case a technique is found achieving high InGaNAs material quality (in particular a suitable high charge carrier lifetime) at MOVPE cost level or lower, this concept is highly attractive in terms of cell performance and also allows extremely thin and low weight cells (upright & lattice matched growth).

In the framework of Impro-33, to our knowledge it was tested for the first time to implement an active Ge junction by MBE (prior to the InGaNAs growth), which would allow to avoid one MOVPE process. In short, the team at TAU/ORC was able to demonstrate smooth III-V-buffers on p-Ge and recorded photovoltaic characteristics for the MBE grown III-V/Ge solar cells, but despite showing future potential, the practical performance for these junctions was not yet sufficient for high efficiency tandem solar cell devices and for the 4J InGaNAs cells the Ge junctions were realized by MOVPE.
In addition, for the InGaNAs material we faced material quality challenges in the first part of the project that led to multiple non-conclusive results having very low V_{OC} and I_{SC} values compared to prior achievements. The solution was found in a contamination within the MBE tool forcing us to perform a comprehensive system overhaul.
Only after this and the standard ramp up program, we were ready for new InGaNAs epitaxy experiments in May 2021. Then, however, we could start making constant progress towards demonstrating high performance InGaNAs junctions on Ge which is shown exemplary for the achieved J_{SC} values over the experimental trials in figure 3-7.
As an outcome the best InGaNAs junctions grown on top p-Ge templates showed over 90% IQE values, which is comparable or even better than what was earlier achieved by ORC and CESI on p-GaAs. On the latest wafers with the full 4J InGaNAs structure optimized for EOL the electrical performances reached are shown in table 3-4, whereas some further improvements were built in such as a band-gap adaption of the InGaNAs sub-cell.
As the InGaNAs junction still limits the full 4J cell performance, since February 2022 all activities were focused on proving an InGaNAs junction grown on Germanium with the required J_{SC}. By implementation of a narrower Eg and adding a DBR (distributed Bragg reflector) under the InGaNAs junction a short circuit current approaching the target BOL J_{SC}=16.1 mA/cm^2 required for a full 4J cell could be demonstrated finally. However, the irradiation tests performed, show that at EOL conditions (1E15) again the InGaNAs cell becomes the limiting sub-cell (see tables 3-5 to 3-7).

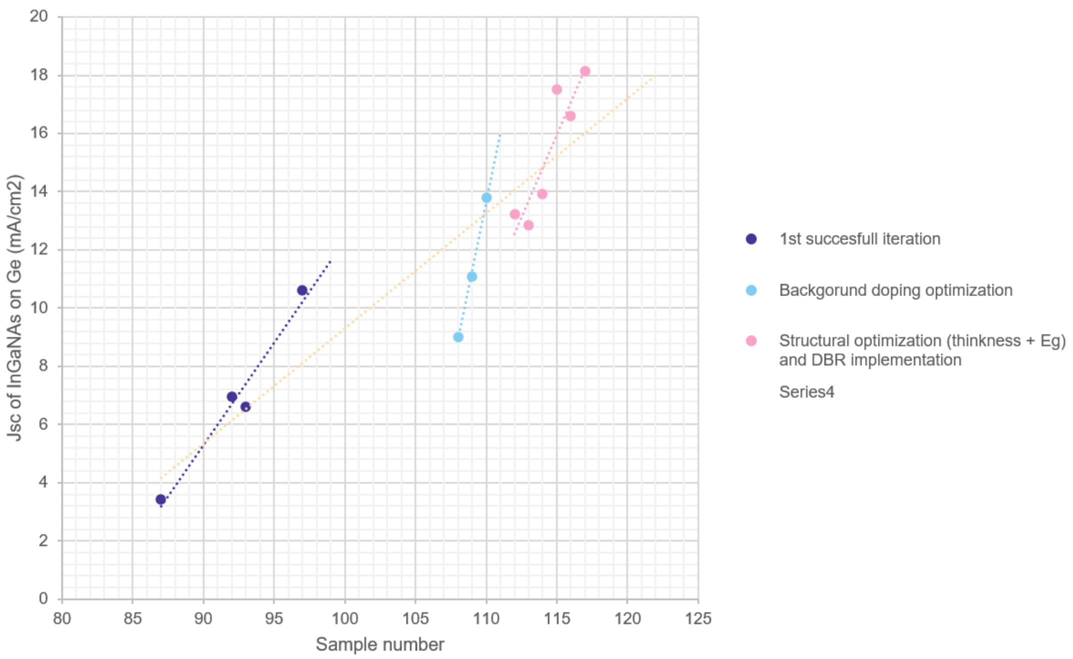


Figure 3-7: J_{SC} values of InGaNAs junctions on Ge vs. sample number.

Table 3-4: Electrical performance (AM0, BOL) of 4J InGaNAs solar cells; EOL design

Sample ID	Jsc [mA/cm²]	Voc [V]	Pmax [mW]	FF [-]	Eff. [%]
R7083	12.8	2.968	107	0.71	19.6

Table3-5: Electrical BOL performance of InGaNAs isotype solar cells (2x2 cm²)

Cell No.	Jsc [mA/cm2]	Voc [mV]	Eff. [%]
AVG (4 cells)	15.5	432	2.97
Best cell	15.8	454	3.08

Table3-6: Electrical EOL (1E15) performances of InGaNAs isotype solar cells (2x2 cm²)

Cell No.	Jsc [mA/cm²]	Voc [mV]	Eff.[%]
AVG (4 cells)	12.5	408	2.19
Best cell	12.9	0.427	2.40

Table 3-7: Electrical performances of 2 selected InGaP/InGaAs dual-junction cells before and after irradiation

Cell ID	Status	Isc [A]	Jsc [mA/cm²]	Voc [V]	F.F.	Eff. [%]
RLCTK001_001	BOL	0.422	16.12	2.297	0.84	22.5
	EOL	0.389	14.86	2.207	0.84	19.8
RLCTK001_002	BOL	0.427	16.32	2.296	0.83	22.5
	EOL	0.395	15.09	2.211	0.82	19.8

Therefore, even if InGaNAs isotypes cells with J_{SC} approaching BOL J_{SC}=16.1 mA/cm^2 further development is required to improve the J_{SC} of the InGaNAs junction for EOL conditions.

3.5 Innovative Ge substrates

As the Ge wafer specification in terms of epi-readiness has not changed significantly over the last decade, in the framework of the Impro-33 project Umicore in consultation with the project partners developed novel prototype Ge wafers in order to find out if a more cost effective solution can be applied for III/V space solar cells without or with insignificant impact on product performance. To do so three wafer types have been prepared named ‘basic’, ‘mid-range’ and ‘high-range’.

In the framework of this development the three main parameters TTV (total thickness variation), surface roughness and micro-waviness were investigated, whereas as expected these parameters for all wafer types could not fully reach the reference surface quality due to the streamlined manufacturing processes. However, finally all tree wafer types were delivered and evaluated by the partners AZUR, CESI and FhG ISE. The ‘basic’ type of wafers at all partners did not result in acceptable results, and clearly can be excluded as a future option. In contrast to this, the other two wafer types showed partly promising results, which is briefly discussed and summarized in the following.

Epitaxy and cell processing at AZUR SPACE

At AZUR, the standard 3G30-Adv cell structure was deposited on all three innovative Ge wafer types provided by Umicore as well as on reference wafers. To achieve optimal comparability, all 4 wafer variants were processed simultaneously in the MOVPE reactor within several runs. As mentioned above, the 'basic' type resulted in unacceptable outcome ($\eta_{avg.} \leq 20\%$) whereas the references exhibited a typical performance for standard wafers and '3G30' recipe with $\eta_{avg,ref.} = 29.2\%$ (60 cells). The 'high-range' wafer type shows on all 60 test cells (2x2 cm²) very reproducible results but with a significantly lower performance of $\eta_{avg,high\text{-}range} = 26.0\%$. Unexpectedly, the 'mid-range' wafer type showed up efficiencies ranging from 24.6% to 28.3% resulting in average $\eta_{avg,mid\text{-}range} = 26.0\%$. Based on these results, AZUR considers the innovative Ge substrates as a potentially promising approach. As most probably an efficiency gap compared the reference wafers will remain due to simplified and streamlined wafer process for the innovative substrates, the cost-effectiveness aspects need to be taken into account for further implementation in further development activities.

Epitaxy and cell processing at CESI

At CESI, the three innovative substrates types were used to grow standard 'CTJ30' solar cells by inserting them in production batch together with standard substrates. Even if the morphology of innovative wafers is definitely affected, 'mid-range' and 'high-range' wafers were considered suitable for cell manufacturing while the basic substrates show significant performance losses. The relative variation of electrical performance parameters between standard and innovative substrates are shown in table 3-8.

Table 3-8: Relative deviation of electrical performance of innovative Ge wafers compared to standard ones

Substrate type	ΔJsc	ΔVoc	ΔFF	ΔEff.
'Basic'	-0.26	-2.46	-4.31%	-4.14%
'Mid-Range'	0.14	-0.31	-0.35%	-0.42%
'High-range'	0.81	-0.14	-0.11%	-0.29%

Epitaxy at ISE (cell processing by AZUR)

At FhG-ISE initially the effect of the III-V nucleation was evaluated and compared for all three inno. wafer types to reference wafers with Umicore's std. "epi-ready" surface. Therefore, double hetero structures were deposited first. Based on first promising results, in a next step 3J solar cell structures were grown. All cells of the "basic" type showed severe shunting effects. The LIV curves (AM0, 25°C) of the other two types and references measured at FhG-ISE CalLab are is shown in figure 3-8. A slight reduction in V_{OC} of approx. 50 mV and a reduced FF for the inno. substrates is observed, while the current density is on target level. Surprisingly, the "mid-range" slightly outperforms the "high-range" wafer. EL images (not shown here) indicate a less uniform surface, potentially correlated to an increased defect density in addition to the higher roughness. However, in summary, the inno. Ge wafer "mid-range" & "high-range" surfaces to reduce wafer costs seem promising, but the surface preparation should be further developed.

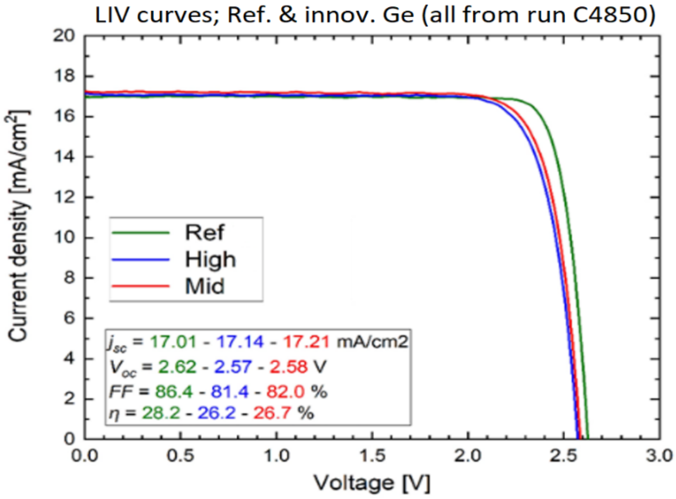


Figure 3-8: Light IV curves of 2x2 test cells made on references, 'Mid-range' and 'High-range' innov. Ge wafers

4 Summary

Within the Impro-33 development activity, a number of different III-V multi-junction solar cell concepts was evaluated comprising also novel growth substrates. Even though due to COVID-19 measures and technological impacts we had to face some significant delays in terms of the initially planned project schedule, major technology development results were achieved that provide important inputs for definition and establishing of further European space solar cell products thus help European industry to stay competitive on the highly competitive and technologically driven space solar cell market. A summary on the project achievements is given in table 4-1.

Table 4-1: Project performance targets, requirements and finally achieved values within Impro-33

Targeted key performance factor	Required performance value	Achieved performance in Impro-33	Investigated cell concept
BOL AM0 efficiency: 35%	*30%*	*32.4%*	*UMM-4J*
EOL AM0 efficiency: 33%	*26%*	*n.a.* *(up to 32% when full device developed)* *n.a.* *(up to 31.9% when InGaNAs is fully developed)*	*Future UMM* *Future InGaNAs 4J*
Area related cell mass: 20 mg/cm²	*50 mg/cm²*	*14.1 mg/cm²* *20 mg/cm²*	*IMM-4J cells* *Taiko-grinded 3G30 cells*
Mechanically flexible SCA's	*(no specific value)*	*Bowing to R = 50 mm without damage*	*50µm 3G30 cell with 50µm cover glass*