# PATHWAYS TO NEXT GENERATION SPACE SOLAR CELLS

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## ABSTRACT

III-V multi-junction solar cells have taken over the lead in today's solar cell market for space. Due to the significantly higher efficiencies and higher radiation hardness the higher manufacturing costs in comparison with silicon solar cells are overcompensated. However, the development of the current state-of-the-art triple-junction solar cell for space applications consisting of the material combination $Ga_{0.5}In_{0.5}P/Ga_{0.99}In_{0.01}As/Ge$ has been driven close to its practical efficiency limits of 30%. This marks the end of a long development process which went on for about 10 years.

Any next generation space solar cell with a real chance to enter the market will be most likely based on a significantly different concept. Several pathways are currently under investigation. This paper presents concepts currently under discussion – their advantages and their drawbacks and their challenges to turn into a commercial product.

## INTRODUCTION

Since the beginning of space exploration by spacecrafts, photovoltaics played the most important role for the power generation of on board instruments. For many years the space market was almost exclusively dominated by silicon (Si) solar cells. Only since the beginning of the 90ies the situation started to change. III-V GaAs cells began to enter the market and finally outrun the Si based technology especially after the development and introduction of III-V multi-junction cells.

This success story is mainly related to the higher conversion efficiencies of III-V multi-junction solar cells and the higher radiation hardness towards particle irradiation like protons and electrons. Both characteristics of III-V multi-junction cells result in higher specific power given in power/mass or power/area especially at end-of-life (EOL), i.e. after 15 years in geostationary orbit. Since the specific power is inversely proportional to the launch costs of the solar generator the higher manufacturing costs are completely overcompensated by the reduced launch costs.

Currently, the III-V triple-junction cell based on the material combination $Ga_{0.5}In_{0.5}P/Ga_{0.99}In_{0.01}As/Ge$ is the state-of-the-art solar cell used for space application having reached a begin-of-life (BOL) efficiency of about 30 % and remaining factors at EOL of 84%-88% in power taking into account an equivalent 1 MeV electron fluence of $1 \cdot 10^{15}$ $cm^{-2}$.

However, with this value also the practical limit of this band gap combination is reached.

With cost reduction being the predominant development driver, next generation solar cells will have to have higher specific power than the current technology keeping the costs at the same time more or less at the same level. These requirements can only be met by either significantly improved efficiencies or reduced thicknesses or a combination of both.

Several different concepts are currently investigated and developed. In the following, the different concepts are introduced and their advantages, drawbacks and challenges are discussed.

## CONCEPTS FOR NEXT GENERATION SOLAR CELLS

In theory, disregarding all manufacturing related losses of solar cells, the efficiency is solely determined by the temperature, the incident spectrum and the band gap of the semiconductor material used. Thus, one way to identify material or band gap combinations with higher efficiency potentials is to compare them on a pure theoretical basis. Figure 1 shows theoretical efficiency limits of triple-junction solar cells with germanium as a bottom cell (0.66 eV) for different band gap values of top and middle cell. The efficiency limits are calculated with the computer code etaOpt [1] that is based on the detailed balance method first introduced by Shockley and Queisser [2]. Spectrum and temperature were AM0 [3] and 25°C.

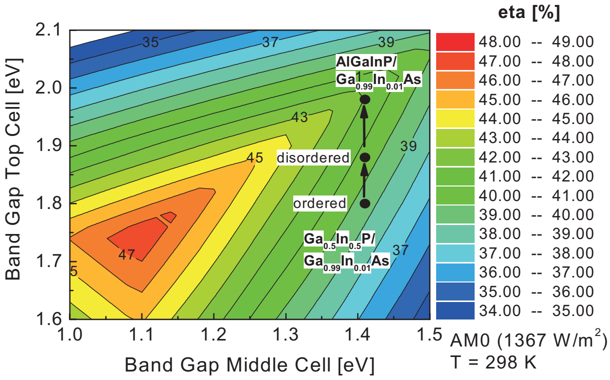

Fig. 1: Theoretical efficiency limits of different band gap combinations of top and middle cell of a 3J cell. The bottom cell is assumed to be germanium with a band gap of 0.66 eV.

As a rule of thumb 70-75% of the theoretical values can be reached in praxis.

Introducing the band gap combinations of the current state-of-the-art 3J solar cell into Figure 1 a theoretical maximum efficiency of 40.6-41.9 % can be obtained. Depending on the top cell manufacturing process which has an influence of the grade of regularity in the crystal and then on the band gap or by the additional introduction of aluminium its band gap can be varied. In any case, the current state-of-the-art 3J cell is far from the optimum band gap combination and as stated before, with about 42 % maximum theoretical efficiency, applying the rule of thumb, the maximum practical efficiency of more or less 30 % is already reached.

The property of the current state-of-the-art 3J cell being non-optimised in terms of maximum theoretical efficiency is related to the fact that this structure is not current-matched. That means not all subcells in the stack provide the same photocurrent. The photocurrent of the bottom cell is in fact almost twice as high as the photocurrent of top and middle subcell which can be seen in Figure 2 where the external quantum efficiencies (EQE) of the different subcells together with their photocurrents under the AM0 spectrum are given.

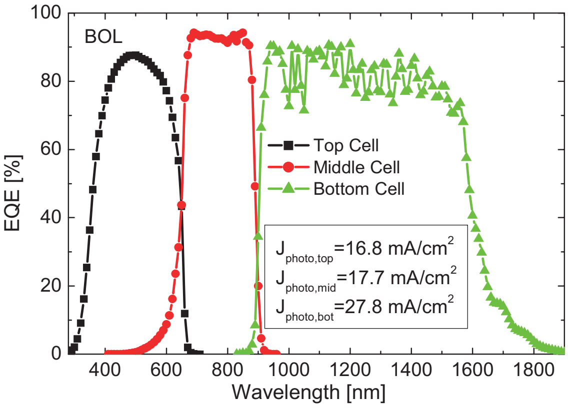

Fig. 2: External quantum efficiency (EQE) of the top, middle and bottom subcell of a triple-junction cell. The photocurrents under the AM0 spectrum show that the bottom cell provides almost twice the current than the other two cells.

This current mismatch is a concession made to the constraint that the structure should be grown lattice-matched which has the advantage that a high material quality is easier to achieve. A lattice-matched structure would also be from a theoretical point of view the most optimum concept for a quadruple cell based on Ge.

This becomes evident when regarding Figure 3. There the theoretical efficiency limits of a quadruple (4J) cell with Ge as a bottom cell (0.66 eV) and $Ga_{0.99}In_{0.01}As$ as the second junction (1.41 eV) in the stack are shown. Obviously, the optimum band gaps for the first and the third junction are 1.98 eV and 1.0 eV, respectively, resulting in an efficiency limit of 51.3 %. Applying the rule of thumb this would translate in a practical efficiency of around 36%.

The first junction can be obtained by an AlGaInP cell which can be grown lattice-matched to Ge while the most promising candidate for the 1 eV material was identified already in 1998 to be GaInNAs [4,5], which can also be grown lattice-matched to the other subcells. Since then a lot of effort was put in developing high quality GaInNAs.

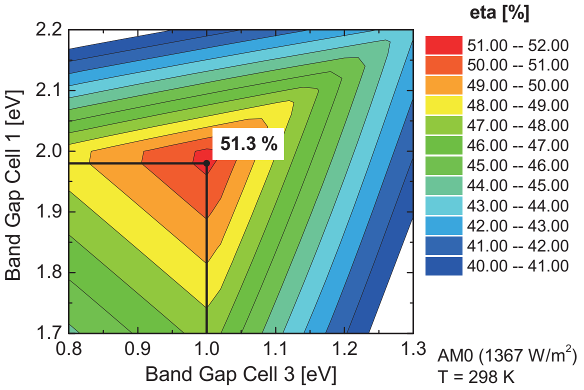

Fig. 3: Theoretical efficiency limits of different band gap combinations of the first and the third cell of quadruple (4J) cell. The bottom cell is assumed to be germanium with a band gap of 0.66 eV and the second cell is $Ga_{0.99}In_{0.01}As$ with a band gap of 1.41 eV.

However, it turned out that this material combination suffers from very poor electrical properties. Figure 4 shows internal quantum efficiencies (IQE) of differently annealed GaInNAs solar cells with an overall thickness of 1 μm under a GaAs filter to simulate the situation in a real 4J cell [6]. By adjusting the annealing conditions after the growth a clear improvement is visible.

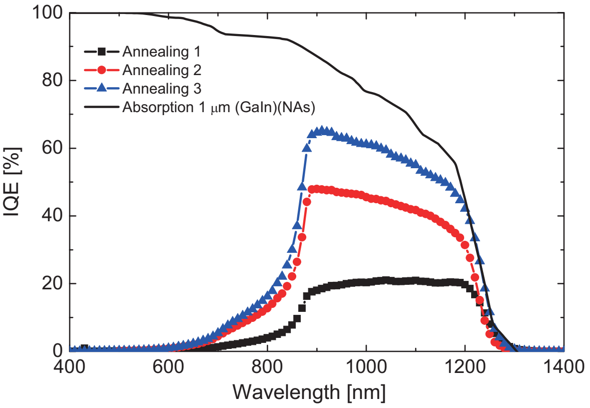

Fig. 4: Internal quantum efficiencies (IQE) of (GaIn)(NAs) solar cells, annealed under different conditions. The light was filtered by a 700 nm thick GaAs cap.

However, diffusion lengths are still not large enough to provide the photocurrent density of 16 mA/cm$^2$ required for a beneficial implementation into a 4J cell. Highest photocurrent densities are still only in the range between 10-12 mA/cm$^2$ for those cells.

Although, there are still research activities going on aiming to improve the electrical properties of this material combination there are also indications which point in the direction that the introduction of nitrogen into GaInAs material – which is necessary to reduce the bandgap – acts like an intrinsic defect. This would suggest that the required material quality might never be reached.

That is why several other approaches are currently under investigation which aim for increasing specific power and/or reduce manufacturing and integration cost. These can be categorised as follows:

1. Enhancement of optical properties by introducing quantum structures, e.g. quantum wells
2. Lattice-mismatched (or metamorphic) approaches
3. Development of thin solar cells
4. Increase of the cell area
5. A combination of all

Starting with the first point, there is still the option to improve the current triple-junction cell structure by introducing modifications, e.g. introducing layers like quantum wells into the structure which aim for improving the current matching conditions.

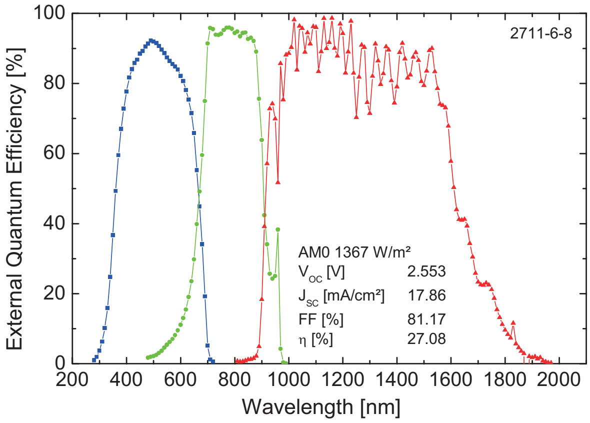

Fig. 5: EQE of top middle and bottom cell of a triple-junction solar cell including quantum well layers in the middle cell.

Figure 5 shows the EQE of a 3J cell which contains quantum wells in the middle cell extending the absorptivity of the middle cell on the expense of the bottom cell current. First results with non-optimised 3J cells including quantum wells show quite promising efficiencies of about 27% under AM0. Although the overall efficiency increase for structures including quantum wells is only in the range of 2% (absolute) this additional layers are quite easy to implement and there is no change in technology required.

A much greater potential for improvement lies in structures where the constraint of lattice-matching is given up. Going back to Figure 1 it can be seen that the highest theoretical values of up to 47.7 % is obtained with a 3J cell based on Ge as bottom cell when the band gap combination would be 1.74 eV for the top cell and 1.1 eV for the middle cell.

Although almost all band gaps between 0.2 eV and 2.5 eV are accessible by III-V compounds (Figure 6), not all combinations can practically be combined without any problems.

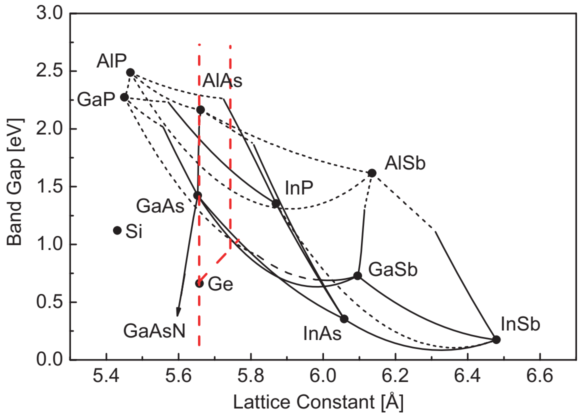

Fig. 6: Band gap versus lattice constant for different III-V material combinations. The dashed lines correspond to the lattice-matched and lattice-mismatched approaches.

From the band gap engineering map of III-V compound semiconductors given in Figure 6 the optimum material combination could be obtained with GaInP and GaInAs both with fairly high indium content. However, the lattice constant of both materials would be slightly different from each other and clearly different from the one of Germanium. Since the different subcells of a 3J cell are grown layer by layer in an epitaxial process on top of each other, differences in lattice-constant cause strain and tensile stress in the material that may lead to defects in the crystal and therefore poor material qualities and also efficiencies. Nevertheless, lattice-mismatched approaches are investigated with the constraint that top and middle cell still have to have the same lattice-constant. In Figure 1 all band gap combinations where this requirement is fulfilled are represented by the dashed line. The structure currently under investigation consists of the material combination of $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ with a theoretical maximum efficiency of 44.5 %.

Besides the improvements in efficiency there is also a trend towards thinner cells which would lead to higher specific power.

In principle there are different ways to obtain thin solar cells which also can be subdivided in the following points:

1. Use of thinner Ge substrates
2. Grinding down the backside of solar cell after epitaxial growth
3. Grinding down before epitaxial growth
4. Substrate removal approaches

All of these points have related problems that have to be solved in order to maintain in the first place a yield that is comparable to the current technology. While the thickness limit for the first point in the list is about 70-100 μm, for the second and third approach one might expect reduced thicknesses of down to 20 μm. Even thinner are the cells that are obtained from carrier removal approaches (5-10 μm).

Figure 7 shows an example of a 100 μm thin solar cell manufactured by Azur Space [7]. Here the thickness is just reduced to a level where the solar cell starts to become flexible, what might have additional advantages for future panel concepts.

Fig. 7: Space solar cell (A=30.18 $cm^2$) on 100 μm thin Ge substrate weighing 1.8 g. The weight reduction compared to 150 μm Ge substrates is 28% [7].

Fig. 8: Photograph of a thin-film six cell string of GaAs single-junction cells [8]. The thickness of one solar cell is less then 5 μm in this case.

Figure 8 shows an example of a solar cell string manufactured at the Radboud University in Nijmegen [8]. The research group there developed a process to remove the solar cells from the substrate without destroying the substrate. So, it could be reused for additional manufacturing runs. Actually, since higher solar cell prices will most likely not be accepted by the market a lift-off process which can be viably incorporated into a commercial mass production line is assumed to be a prerequisite for maintaining or even reducing costs.

Another future trend is the usage of larger cell areas which allows a reduction of the integration costs since then only half of the number of solar cells have to be handled (see Figure 9).

Fig. 9: Large area triple-junction space solar cell (8cm x 8cm with cropped corners) [7].

Finally, as it was mentioned before the most probable design of a next generation solar cell will be a combination of several points. Thereby, a quite interesting approach is the inverted metamorphic solar cell [9] (cp. Figure 10).

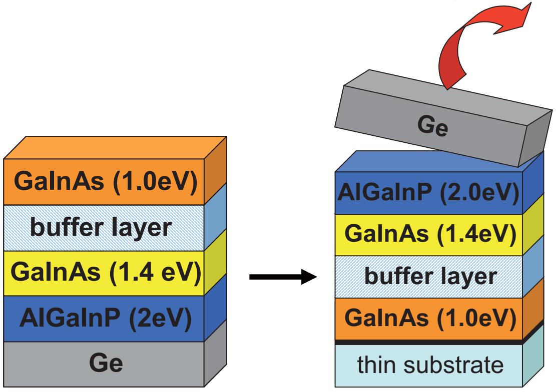

Fig. 10: Inverted metamorphic 3J solar cell. The cell is grown upside down on a Ge (or GaAs) substrate which is removed in a later step.

A 3J solar cell is here grown upside down on a Ge (or GaAs) substrate. That means Ge in this case is no longer a subcell of the device. The material combination in this case is AlGaInP/GaInAs/GaInAs with a band gap combination of 2.0eV/1.4eV/1.0eV. Therefore, the In content of the last cell to be grown has to be increased significantly which also results in an increase of the lattice constant. The advantage of this approach is that the most delicate subcells – the top and the middle cell – in the stack are still grown lattice-matched to Ge maintaining a very high material quality comparable to those in the current 3J cell structure. Since in this design the bottom cell has a higher band gap of 1.0 eV, higher efficiencies of about 33-34 % should be achievable in praxis under AM0. After growth the metallization of the top side of the cell is made and the cell is placed on a thin substrate. Then, the Ge substrate has to be removed (cp. Figure 10).

However, also in this approach a proper lift-off process which allows the reuse of the substrate is assumed to be a prerequisite to avoid a significant increase of the manufacturing costs

## SUMMARY

The current 3J cell concept based on the lattice-matched material combination $Ga_{0.5}In_{0.5}P/Ga_{0.99}In_{0.01}As/Ge$ is driven to its practical efficiency limit of about 30 %. Several concepts of next generation solar cells which will have the constraints to be not higher in price than the current 3J cells, but provide a higher specific power, have been introduced. The lattice-matched 4J cell would be the optimum solution. However, the 1eV semiconductor material which would be best suited - GaInNAs – seems to have some intrinsic defects which might not allow reaching the required material quality. Other approaches are currently investigated of which the most promising candidates are lattice-mismatched approaches and thinner cell concepts or a combination of both. Here, the inverted metamorphic concept seems to be already quite advanced. However, as long as a proper cost-effective lift-off technique is not found which allows the reuse of the substrate it seems to be difficult to keep the costs within acceptable limits. Going to larger solar cell areas is an obvious option by which integration costs could be reduced.

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# PATHWAYS TO NEXT GENERATION SPACE SOLAR CELLS

Dr. Carsten Baur
Kitakyushu,
6th Space Environment Symposium
29/10/2009

European Space Agency

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## OUTLINE

1. Current status
2. Pathways to next generation solar cells
3. Summary

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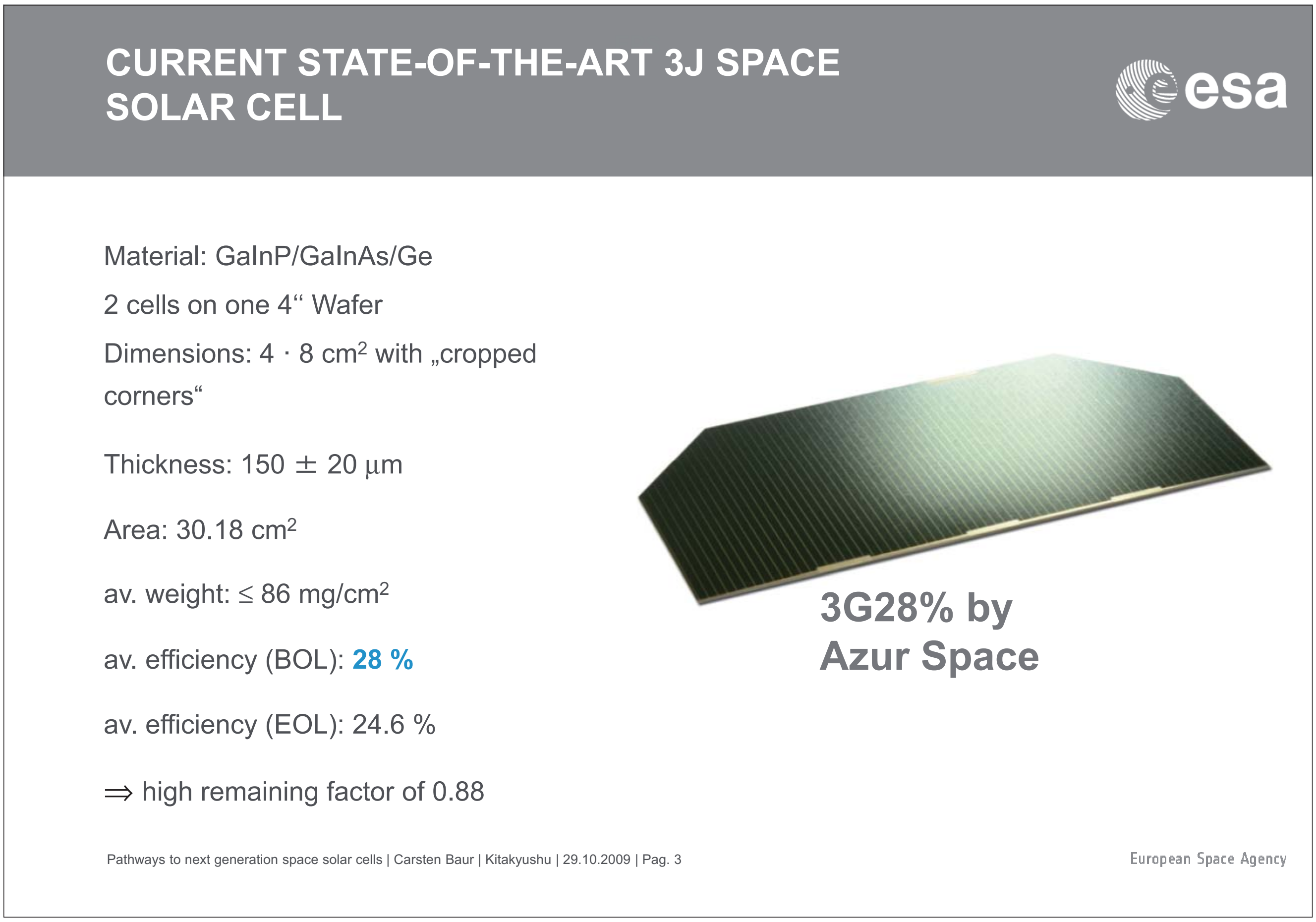

## CURRENT STATE-OF-THE-ART 3J SPACE SOLAR CELL

Material: GaInP/GaInAs/Ge

2 cells on one 4“ Wafer

Dimensions: 4 · 8 $cm^2$ with „cropped corners“

Thickness: 150 ± 20 μm

Area: 30.18 $cm^2$

av. weight: ≤ 86 $mg/cm^2$

av. efficiency (BOL): **28 %**

av. efficiency (EOL): 24.6 %

⇒ high remaining factor of 0.88

**3G28% by Azur Space**

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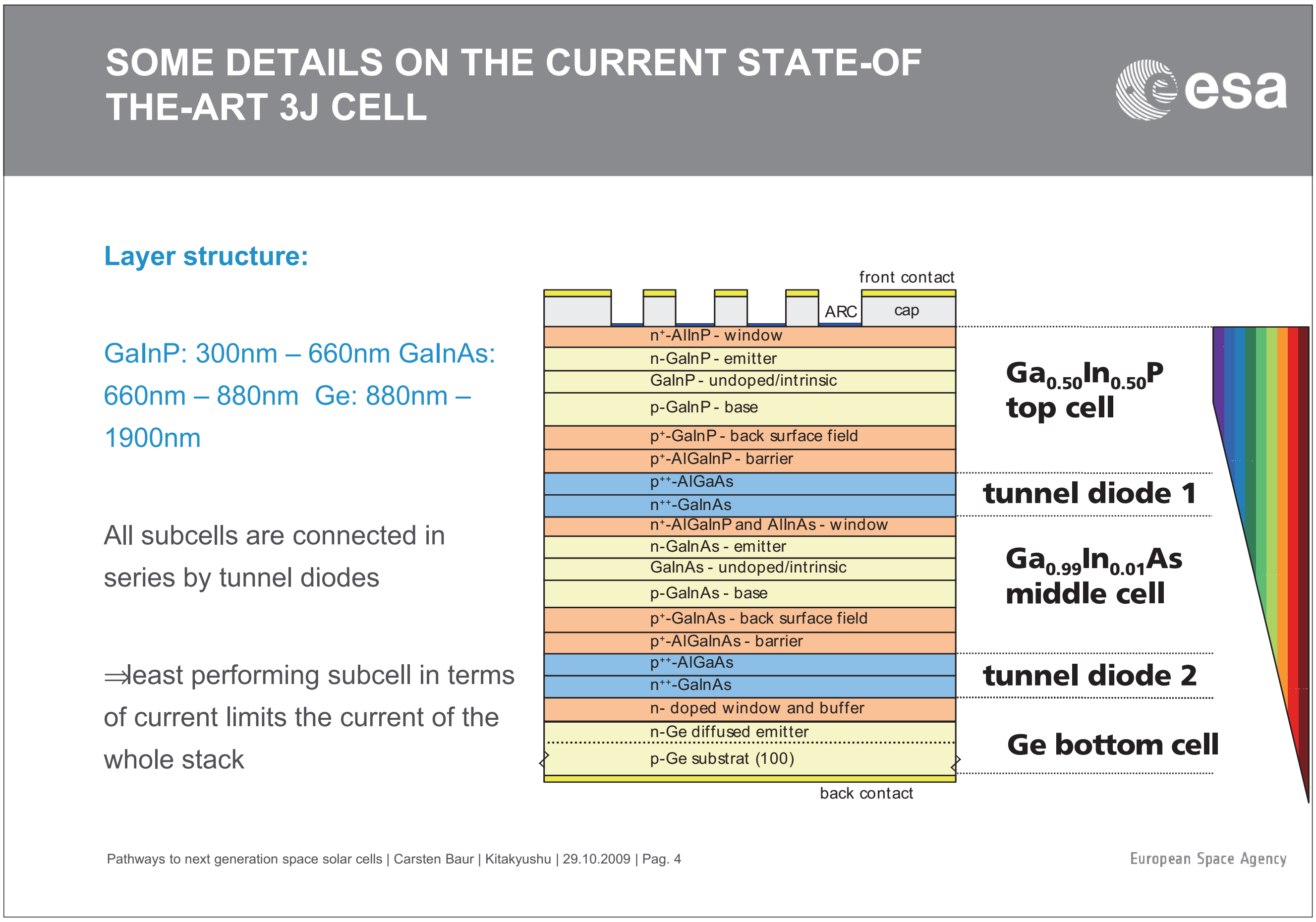

## SOME DETAILS ON THE CURRENT STATE-OF THE-ART 3J CELL

**Layer structure:**

GaInP: 300nm – 660nm GaInAs: 660nm – 880nm Ge: 880nm – 1900nm

All subcells are connected in series by tunnel diodes

⇒least performing subcell in terms of current limits the current of the whole stack

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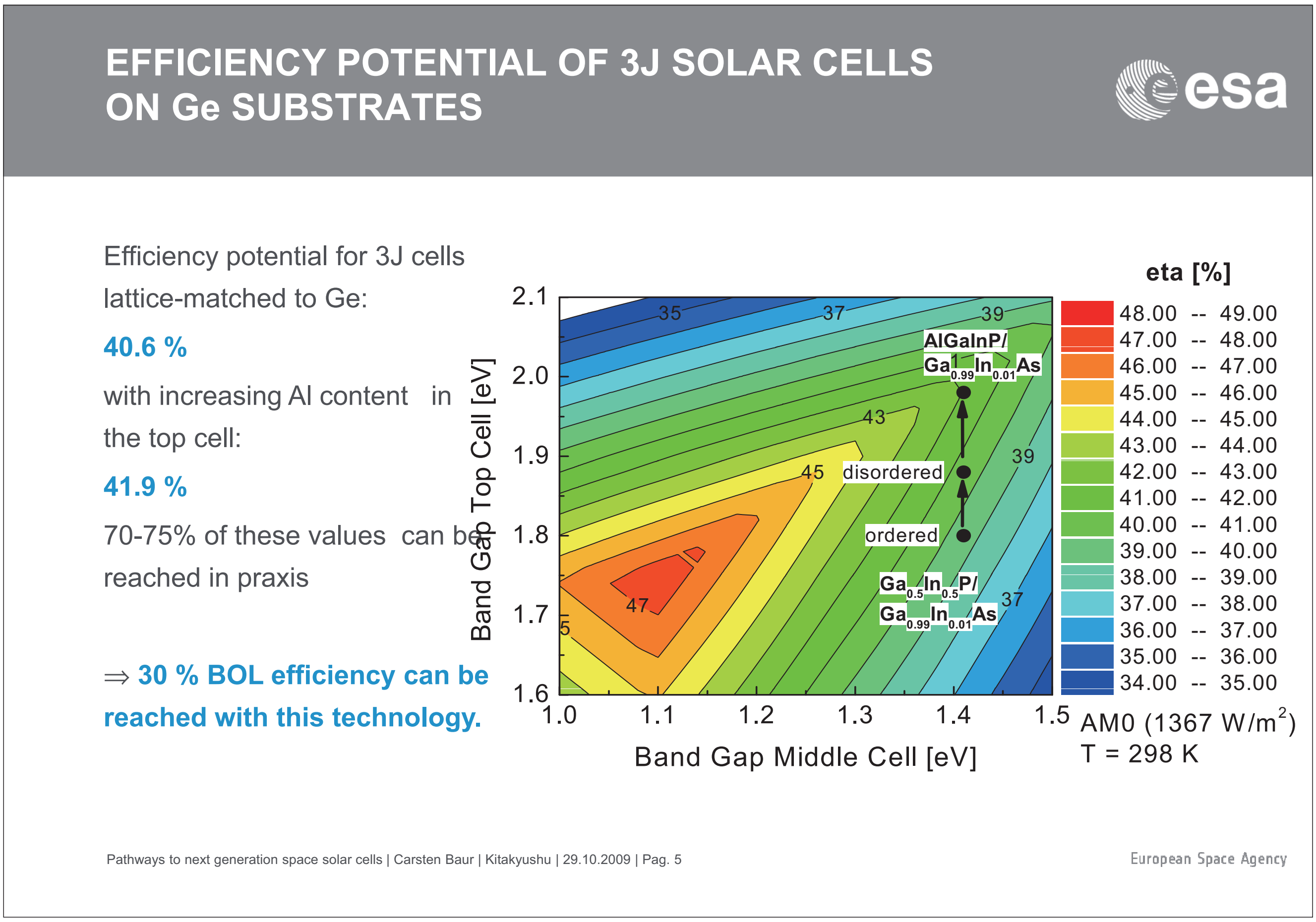


## EFFICIENCY POTENTIAL OF 3J SOLAR CELLS ON Ge SUBSTRATES

Efficiency potential for 3J cells lattice-matched to Ge:

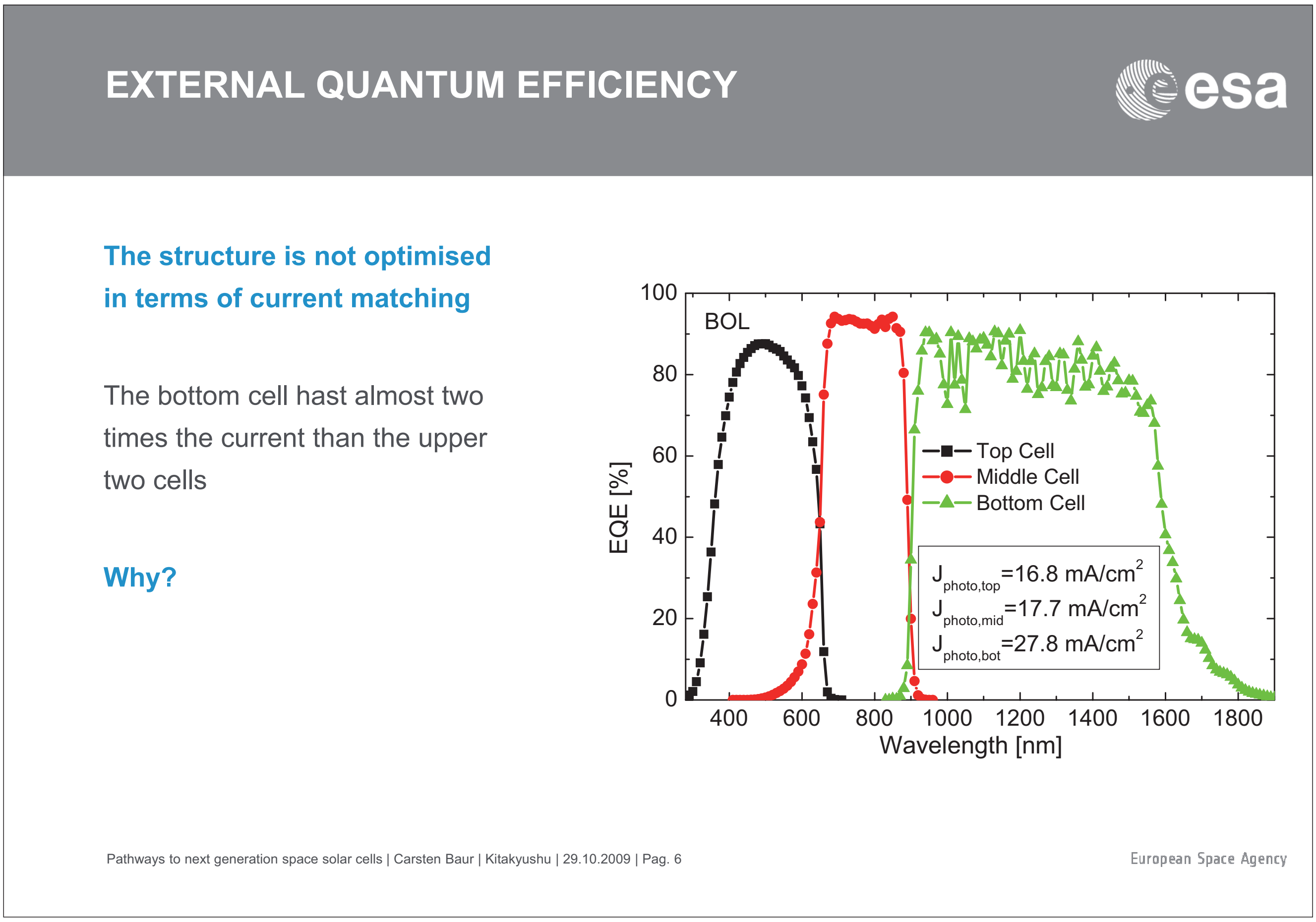
**40.6 %**

with increasing Al content in the top cell:

**41.9 %**

70-75% of these values can be reached in praxis

⇒ **30 % BOL efficiency can be reached with this technology.**

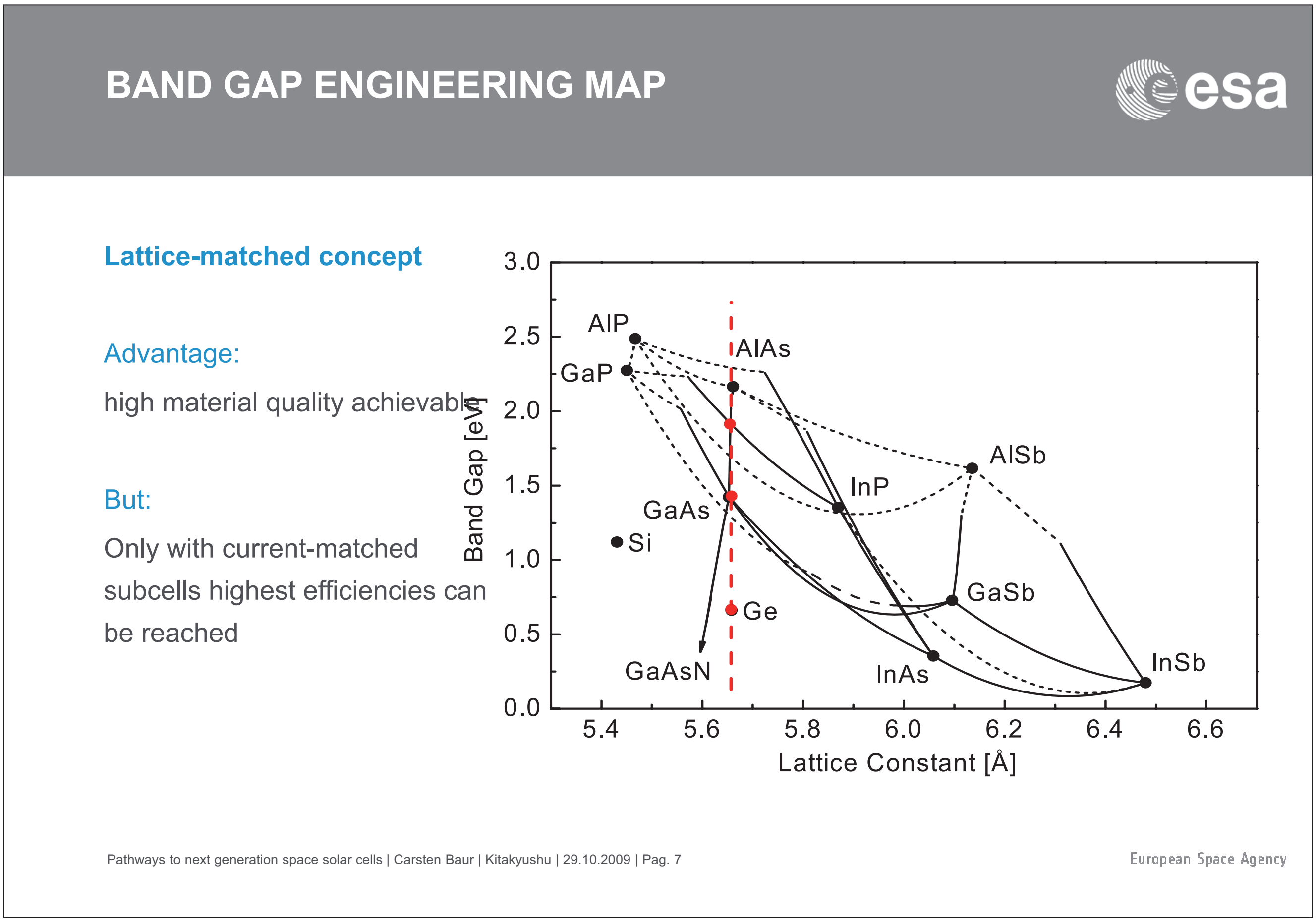


## EXTERNAL QUANTUM EFFICIENCY

**The structure is not optimised in terms of current matching**

The bottom cell hast almost two times the current than the upper two cells

**Why?**



## BAND GAP ENGINEERING MAP

**Lattice-matched concept**

Advantage:

high material quality achievable

But:

Only with current-matched subcells highest efficiencies can be reached

## SUMMARY OF CURRENT SITUATION

1. The current state-of-the-art solar cell type is based on the “lattice-matched” GaInP/GaInAs/Ge triple-junction solar cell
2. The maximum practically achievable efficiency of 30% begin of life (BOL) and about 25% end of life (EOL) is or is soon to be achieved by all three major manufacturers of space solar cells based on III-V high efficiency solar cells (Azur Space GmbH, Emcore, Spectrolab)
3. A development process of improvements and fine-tuning of the structure which lasts more than 10 years has come to an end!

**What will be the next generation?**

## REQUIREMENTS FOR NEXT GENERATION SOLAR CELLS

### COSTS REDUCTION

1. Cost of the solar cell itself and its integration on the panel
   ⇒ improvement of manufacturing and integration processes

2. Launch costs
   ⇒ increase of the power/mass or power/area ratio of the solar cell by
   a. increase of efficiency
   b. reduction of mass

New solar cell technologies only have the chance to enter the market when there is a real overall cost reduction taking into account 1. and 2.

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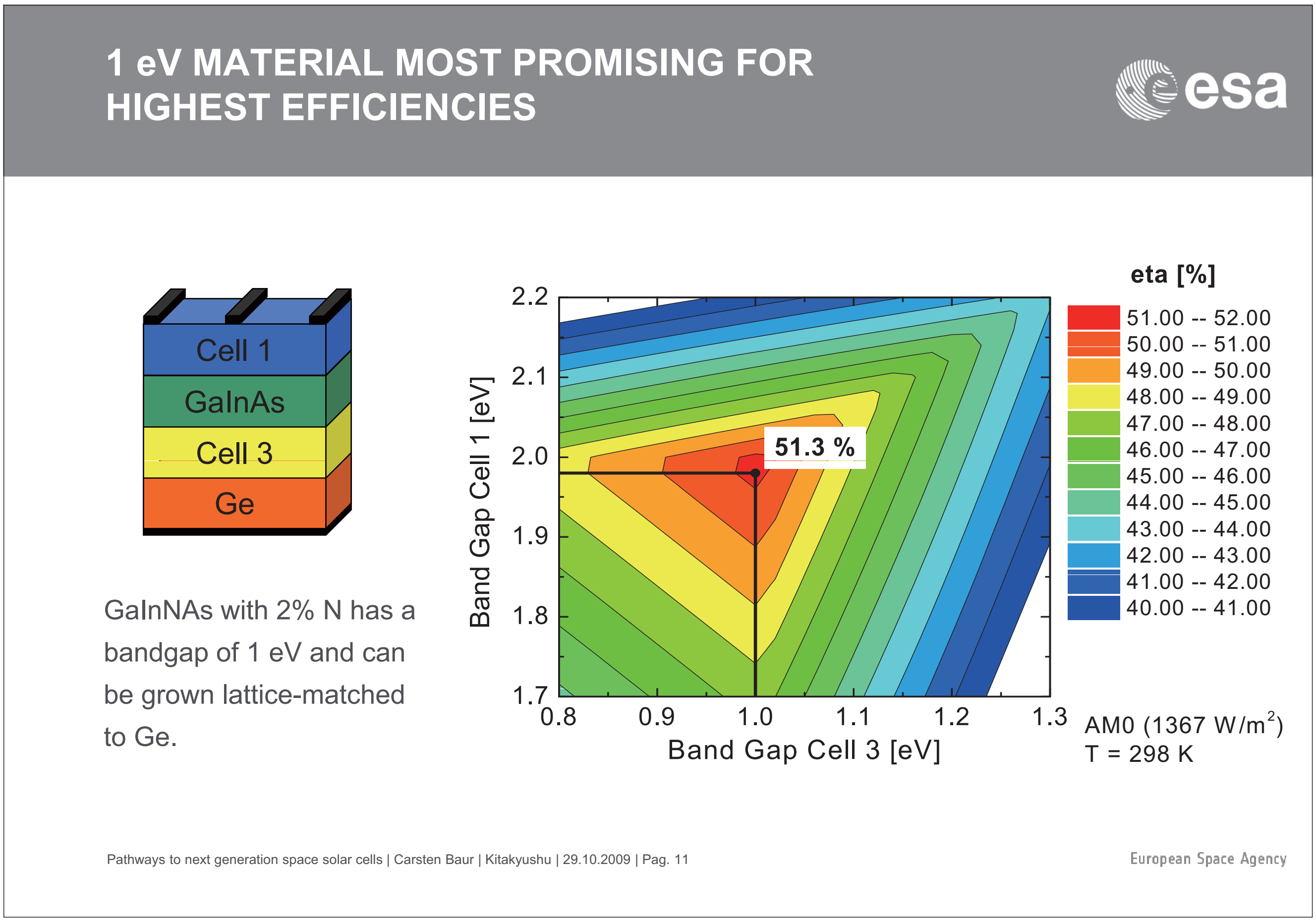
## MOST PREFERRED SOLUTION

### 4J CELL BASED ON Ge

Target:

Find a semiconductor material that can be grown lattice-matched to Ge and takes half the current of the Ge subcell.



## 1 eV MATERIAL MOST PROMISING FOR HIGHEST EFFICIENCIES

GaInNAs with 2% N has a bandgap of 1 eV and can be grown lattice-matched to Ge.

AM0 (1367 W/m$^2$)
T = 298 K

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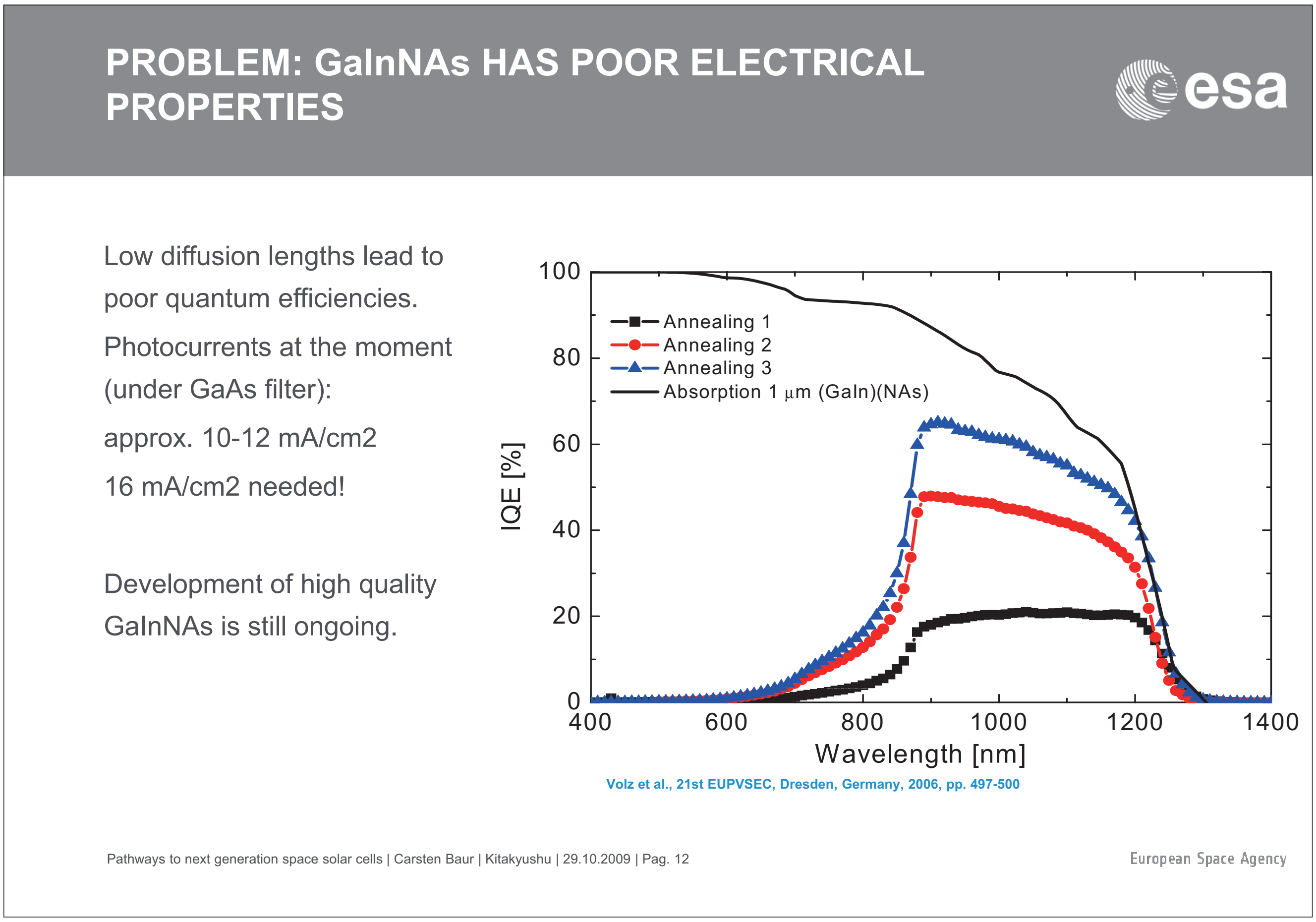

## PROBLEM: GaInNAs HAS POOR ELECTRICAL PROPERTIES

Low diffusion lengths lead to poor quantum efficiencies.

Photocurrents at the moment (under GaAs filter):

approx. 10-12 mA/cm2

16 mA/cm2 needed!

Development of high quality GaInNAs is still ongoing.

Volz et al., 21st EUPVSEC, Dresden, Germany, 2006, pp. 497-500

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## OTHER OPTIONS

1. Enhancement of optical properties by introducing quantum structures, e.g. quantum wells
2. Lattice-mismatched (or metamorphic) approaches
3. Development of thin solar cells
4. Increase of the cell area
5. Combination of the points mentioned above

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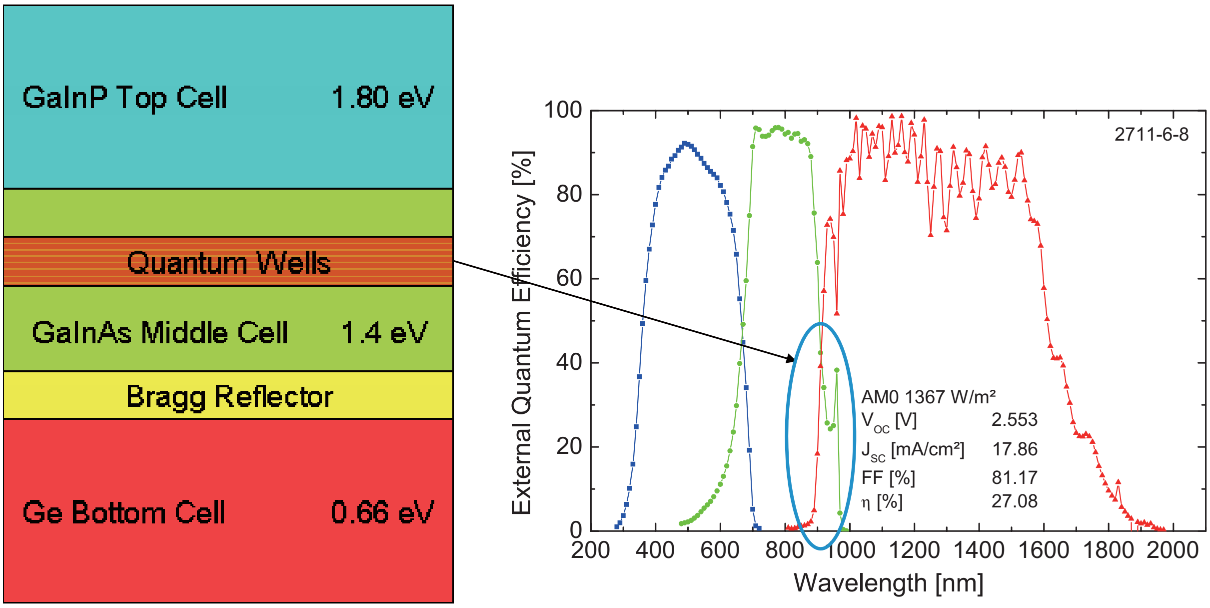
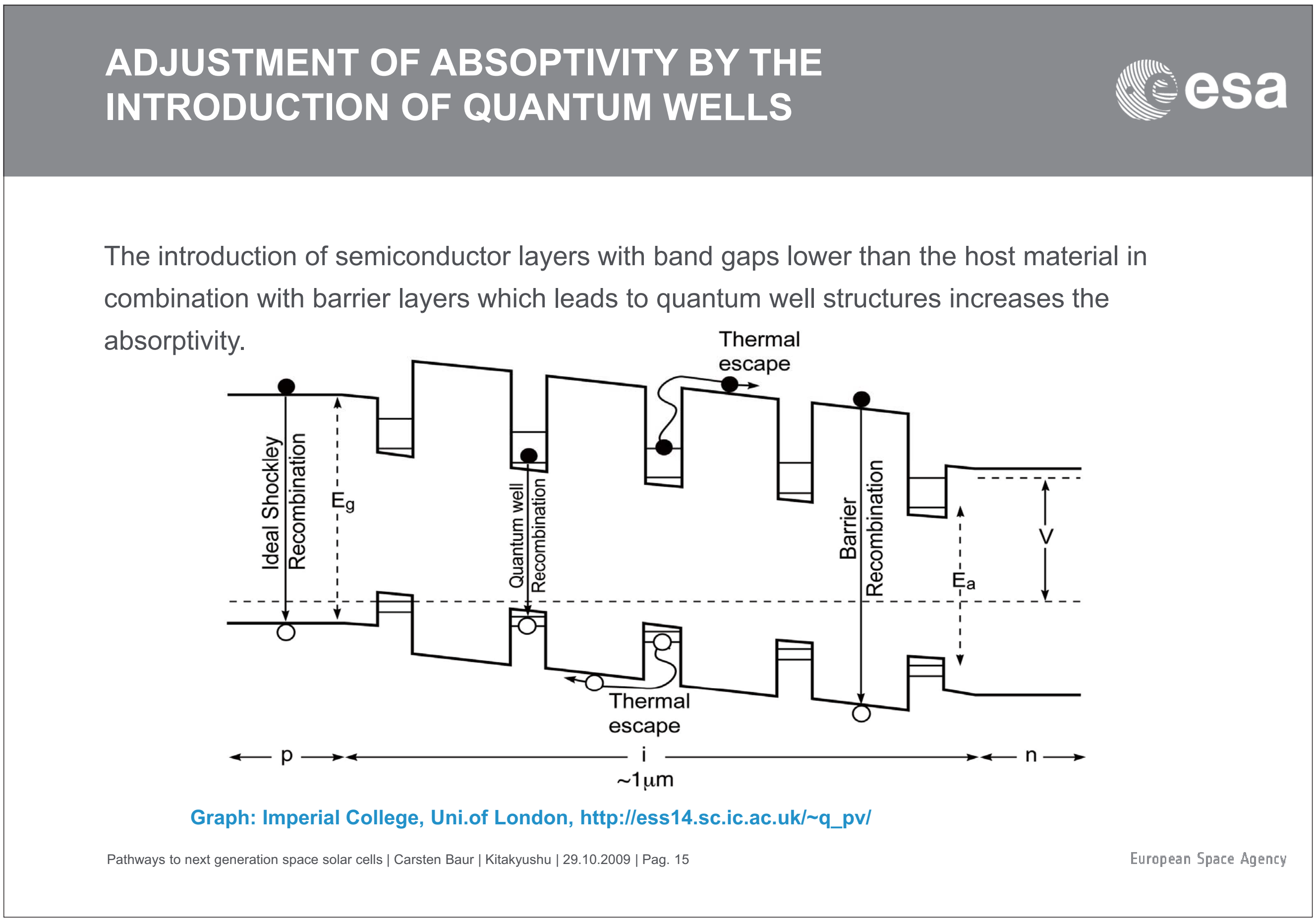
## ENHANCEMENT OF ABSOPTIVITY BY THE INTRODUCTION OF QUANTUM WELLS

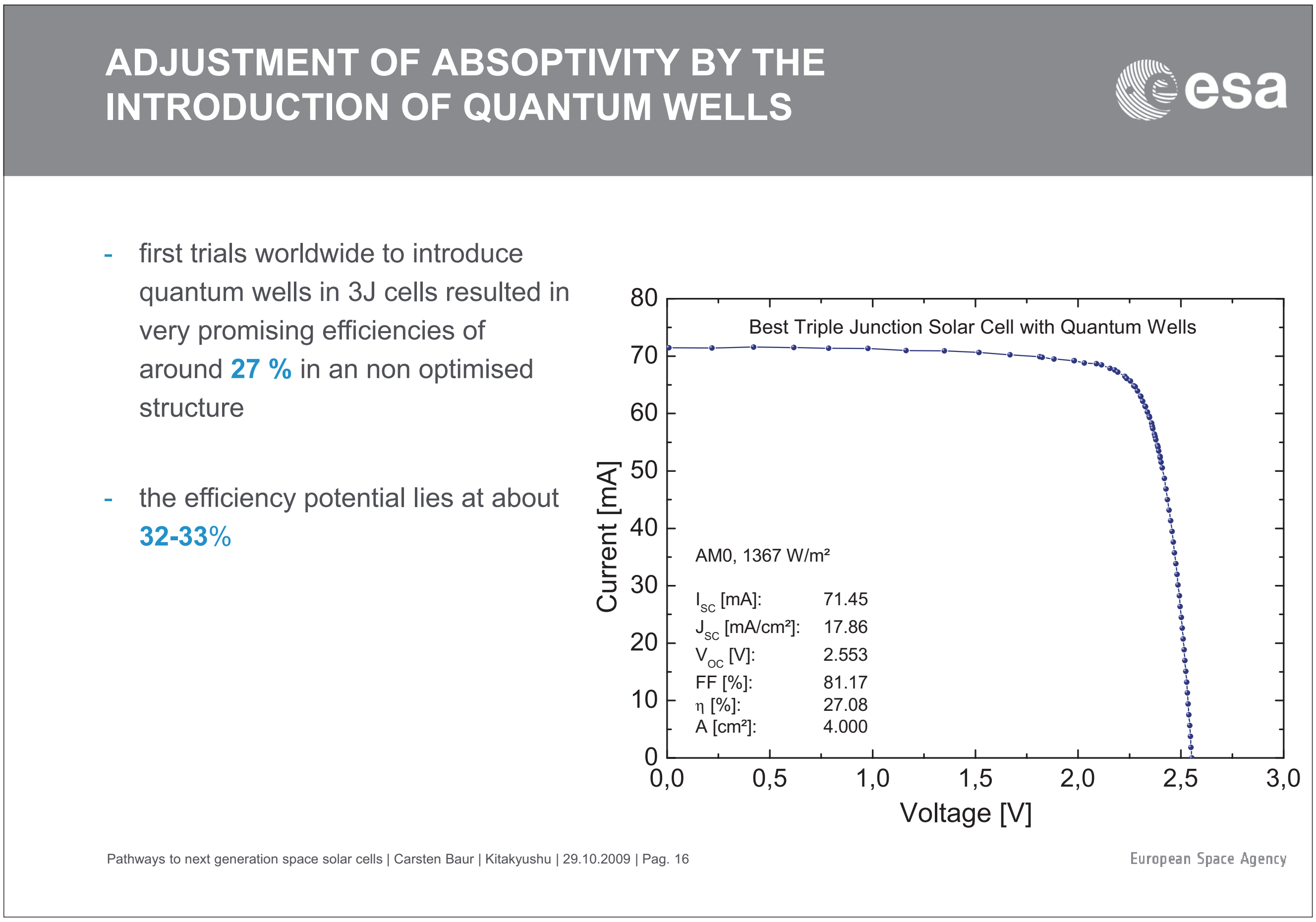




## ADJUSTMENT OF ABSOPTIVITY BY THE INTRODUCTION OF QUANTUM WELLS

The introduction of semiconductor layers with band gaps lower than the host material in combination with barrier layers which leads to quantum well structures increases the absorptivity.

Graph: Imperial College, Uni.of London, http://ess14.sc.ic.ac.uk/~q_pv/



## ADJUSTMENT OF ABSOPTIVITY BY THE INTRODUCTION OF QUANTUM WELLS

- first trials worldwide to introduce quantum wells in 3J cells resulted in very promising efficiencies of around **27 %** in an non optimised structure
- the efficiency potential lies at about **32-33%**

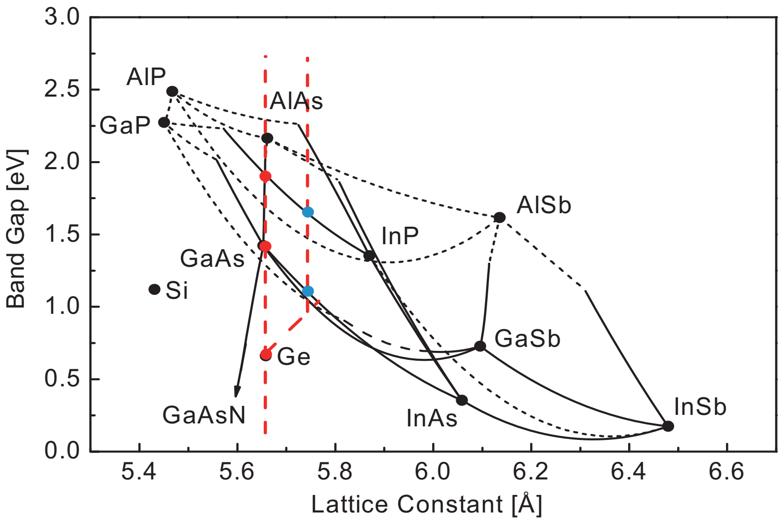
AM0, 1367 W/m²

| | |
|---|---|
| $I_{SC}$ [mA]: | 71.45 |
| $J_{SC}$ [mA/cm²]: | 17.86 |
| $V_{OC}$ [V]: | 2.553 |
| FF [%]: | 81.17 |
| η [%]: | 27.08 |
| A [cm²]: | 4.000 |

## BAND GAP ENGINEERING MAP

**Problem:** Strain is introduced into the structure which can lead to threading dislocations and poor material quality

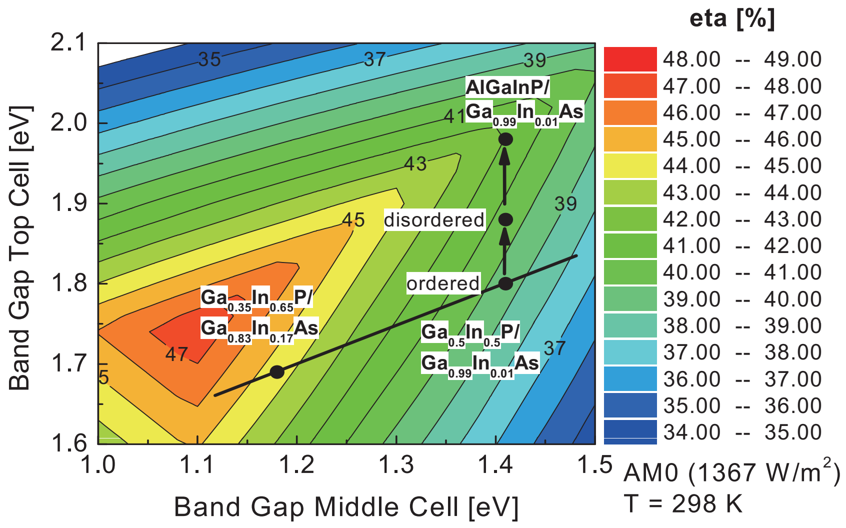
**Solution:** buffer layers to relax the strain



## LATTICE-MISMATCHED APPROACH

Lattice-mismatched or metamorphic approach allows higher efficiencies for Ge based 3J cells.

Efficiency limit (theoretical): **44.5 %**



AM0 (1367 W/m$^2$)
T = 298 K

## WAYS TO THIN SOLAR CELLS

1. Use of thinner Ge substrates

   **Problems:** handling and yield (cost!!), thickness limit around 100 µm

2. Grind down backside of solar cell after epitaxial growth

   **Problem:** thickness limit around 20 µm, yield (cost!!)

3. Put substrate on support structure and grind down before epitaxial growth

   **Problem:** removal of substrate from support structure after epitaxial growth (high temperature step), thickness limit around 20 µm

4. Substrate removal approaches → reuse/recycling of substrate

   **Problem:** find a cost effective lift-off process

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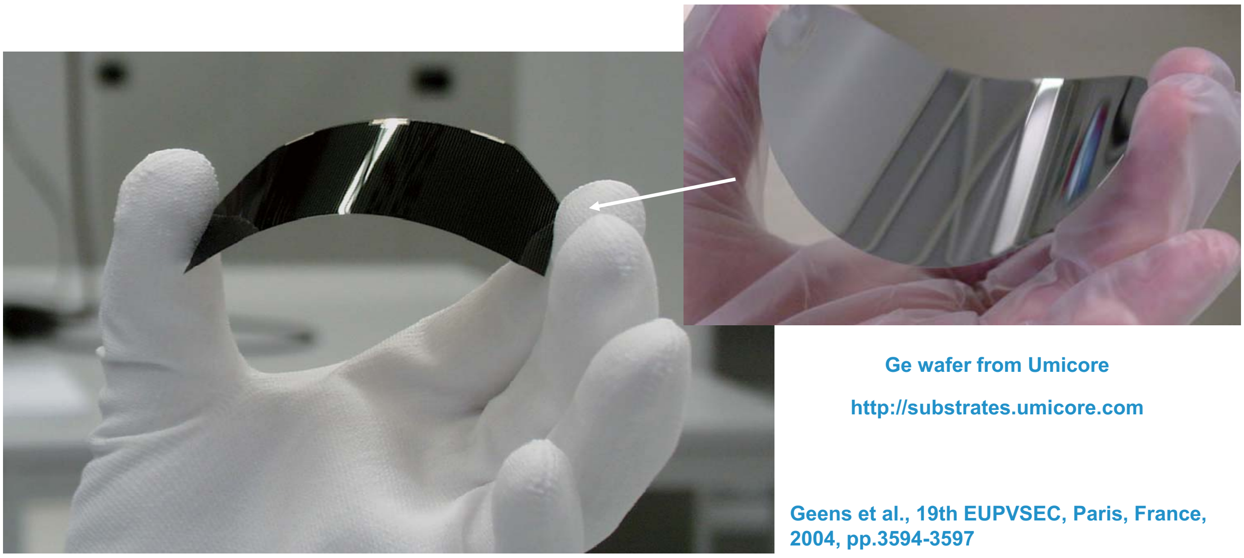
## 3J SOLAR CELLS ON THINNER GE SUBSTRATES (70-100µm)



**Ge wafer from Umicore**

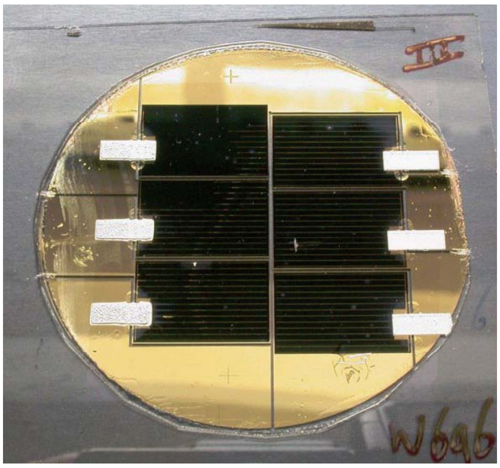
**http://substrates.umicore.com**

**Geens et al., 19th EUPVSEC, Paris, France, 2004, pp.3594-3597**

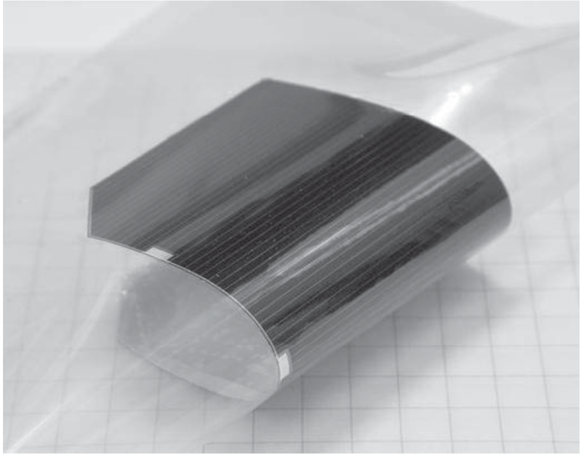
**Geens et. al., 7th ESPC, Stresa, Italy, 2005**

**3J Space solar cell from Azur Space GmbH http://www.azurspace.com/**

## LIFT-OFF CONCEPTS



**Radboud Uni., Nijmegen**



**Sharp Corp.**

**Bauhuis et al., 22nd EUPVSEC, Milano, Italy, 2007**

**Takamoto et al., 19th EUPVSEC, Paris, France, 2004, pp.3689-3691**

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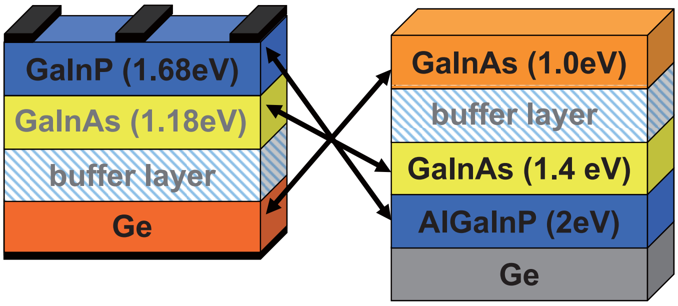
## INVERTED METAMORPHIC 3J SOLAR CELL

Combination of lattice-mismatched approach and substrate removal:

Since the cell is grown upside down on the substrate the fact that the cell is thin is a byproduct of the manufacturing process.

Theoretical efficiency limit: **45-46 %**

realised (Emcore): **32.4%**



metamorphic (conventional)

inverted metamorphic

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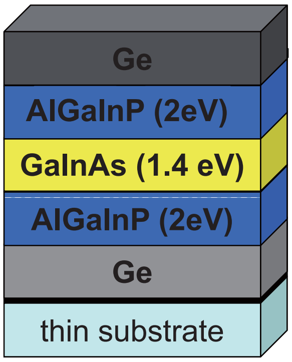

**Ge**

**AlGaInP (2eV)**

**GaInAs (1.4 eV)**

**AlGaInP (2eV)**

**Ge**

thin substrate

inverted metamorphic

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## INCREASE OF SOLAR CELL AREA

Advantages:

- integration cost of solar cells on panels is reduced

Risks:

- Yield decreases due to cell breakage during manufacturing and integration
- higher power loss when cell fails during flight

**Meusel et al., 22nd EUPVSEC, Milano, Italy, 2007, pp. 16-21**

## DISCUSSION

- Efficiency targets discussed here are BOL values. It should be mentioned that the radiation hardness of future cell concepts first has to be demonstrated.

- It is very likely that the next generation solar cell will be in any case significantly thinner than the current structure. However, since a significant part of the whole mass of the solar cell assembly is also the coverglass, this should be adapted accordingly to have a real benefit. The same is true for the underlying structure

- The key development for the next generation solar cell will be that of a cost effective lift-off process. Even if the cell is light-weight and higher in efficiency than the state-of-the-art a significant cost increase will most likely not be accepted by the solar generator manufacturers.

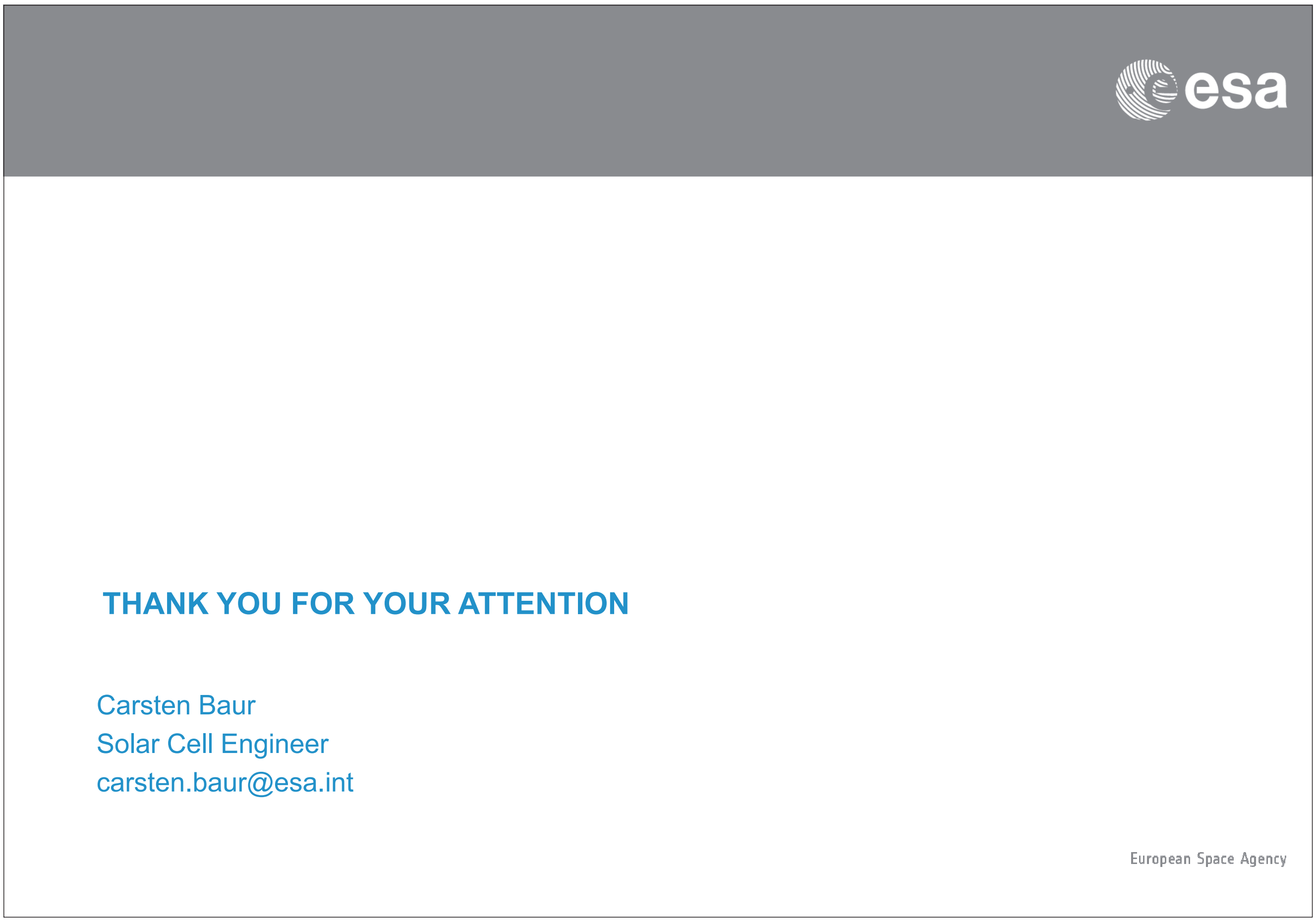
## SUMMARY

- The development of the 3J space solar cell based on the lattice-matched GaInP/GaInAs/Ge concept has reached its practical limits of 30% efficiency.

- Next generation solar cells with a real chance to enter the market shall be ieally light-weight, high-efficient and not higher in cost compared to the current 3J cell.

- Different pathways to achieve this goal have been introduced.

- For thin solar cell concepts the key is the development of a cost effective lift-off process.



## THANK YOU FOR YOUR ATTENTION

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