SOLAR CELL R&D ACTIVITIES AT ESA

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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%.

In order to decrease the overall solar array costs further, new concepts have to be developed and investigated. The European Space Agency (ESA) follows different promising approaches which are firstly related to the increase of solar cell efficiencies. In addition, ways to reduce the cell thickness are investigated in order to bring down the specific power given in power/mass. Finally, larger cell areas could lead to cost savings in the integration process of the solar cells onto the panel substrate.

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 of these material combinations. Both characteristics of the 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 alone 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. Thus, to reduce costs of the solar array further, new designs leading to higher efficiencies have to be developed, together with ways to reduce manufacturing costs of the given and future concepts. Those points are reflected in various R&D activities run by the European Space Agency (ESA) which are discussed in this paper.

WAYS TO HIGHER CONVERSION EFFICIENCIES

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] 25°C. As a rule of thumb 70-75% of the theoretical values can be reached in praxis.

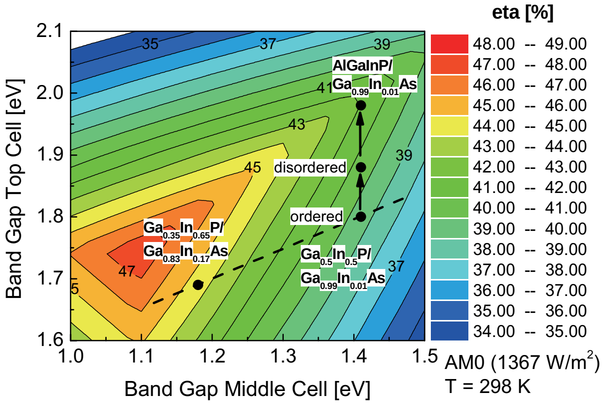

Fig. 1: Theoretical efficiency limits of different band gap combinations of top and middle cell of a 3J cell. The bottom cell is assumed to be germanium with a band gap of 0.66 eV.

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 highest theoretical values of up 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 2), not all combinations can practically be combined without any problems.

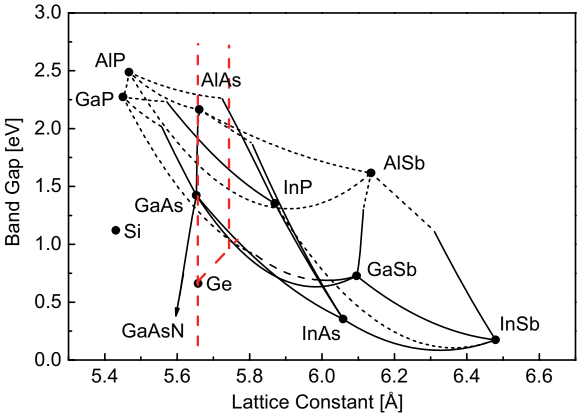

Fig. 2: Band gap versus lattice constant for different III-V material combinations. The dashed lines correspond to the lattice-matched and lattice-mismatched approaches.

From the band gap engineering map of III-V compound semiconductors given in Figure 2 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 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 %.

Apart from this lattice-mismatched approach another idea to increase efficiencies of the lattice-matched design is to add additional junctions to the structure. Since the Ge subcell of the current 3J cell has just twice the current of the top and the middle cell it is quite obvious to introduce a junction between the middle and the bottom cell that just absorbs half of the Ge bottom cell in the current 3J cell design. This would result in a current matching of all subcells leading to very high efficiencies.

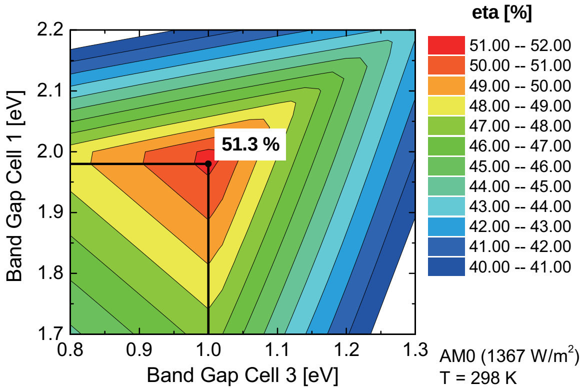

Fig. 3: Theoretical efficiency limits of different band gap combinations of the first and the third cell of quadruple (4J) cell. The bottom cell is assumed to be germanium with a band gap of 0.66 eV and the second cell is $Ga_{0.99}In_{0.01}As$ with a band gap of 1.41 eV.

Figure 3 shows the 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. 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 %. The first junction can be obtained by an AlGaInP cell 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. However, it turned out that this material combination suffers from very poor electrical properties.

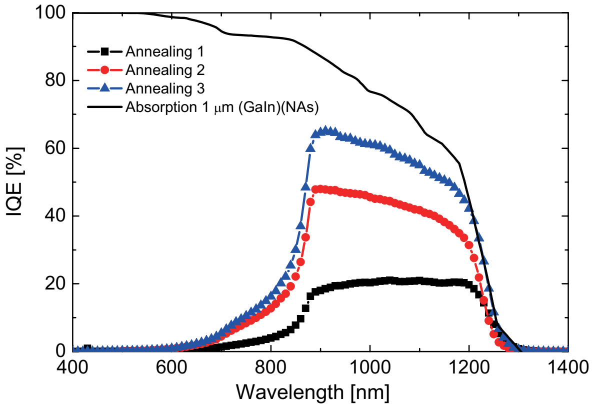

Fig. 4: Internal quantum efficiencies (IQE) of (GaIn)(NAs) solar cells, annealed under different conditions. The light was filtered by a 700 nm thick GaAs cap.

Figure 4 shows internal quantum efficienies (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.

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.

With the long-term target of developing the 4J cell as intermediate steps on this path the quintuple (5J) and sextuple (6J) cell are under consideration.

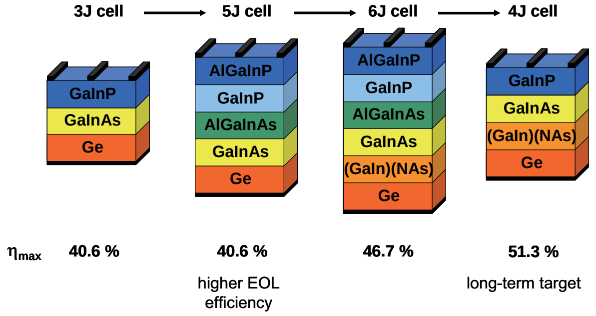

Fig. 5: Roadmap to higher efficiencies of lattice-matched solar cell designs. The 5J and 6J cell are considered intermediate steps on the long-term target of developing the current-matched 4J cell.

Starting from the 3J cell, the 5J cell is obtained by splitting each of the top two junctions of the 3J cell into two. Thereby, the current of a 5J is halved while voltage is doubled. The BOL efficiency of this 5J cell will be identical to the current 3J cell. The benefit of the 5J cells should become visible EOL where the thinner absorber layers are likely to improve the radiation hardness compared the 3J cell which was already shown in first experiments [7].

From the 5J cell then it is only a small step to the 6J solar cell. Since the current is halved, only 8 mA/cm^2 are now required from the GaInNAs subcell in order to make a contribution to the overall efficiency. With the values reached so far it should be feasible to introduce the GaInNAs subcell already. The 6J cell would then have clearly higher BOL and EOL efficiencies. The overall roadmap for the lattice-matched approach is summarized in Figure 5 [8].

OTHER COST REDUCTION ACTIVITIES

Other possibilities to reduce launch, manufacturing and integration costs are identified in thinning down the solar cell structure or to increase their area.

There are different ways to obtain thin solar cells which are investigated in various research activities followed by ESA:

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 6 shows an example of a 100 µm thin solar cell manufactured by Azur Space [8]. 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.

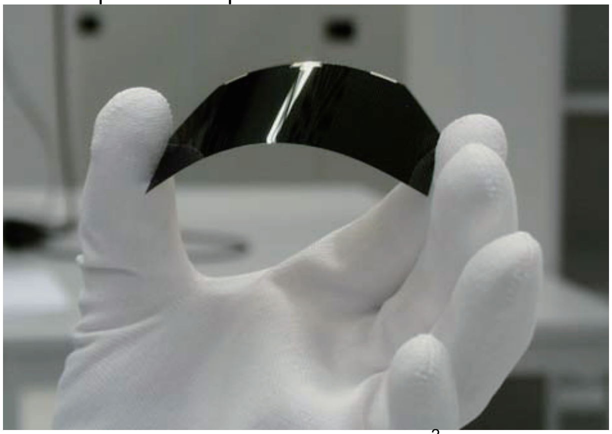

Fig. 6: Space solar cell (A=30.18 cm^2) on 100 µm thin Ge substrate weighing 1.8 g. The weight reduction compared to 150 µm Ge substrates is 28% [8].

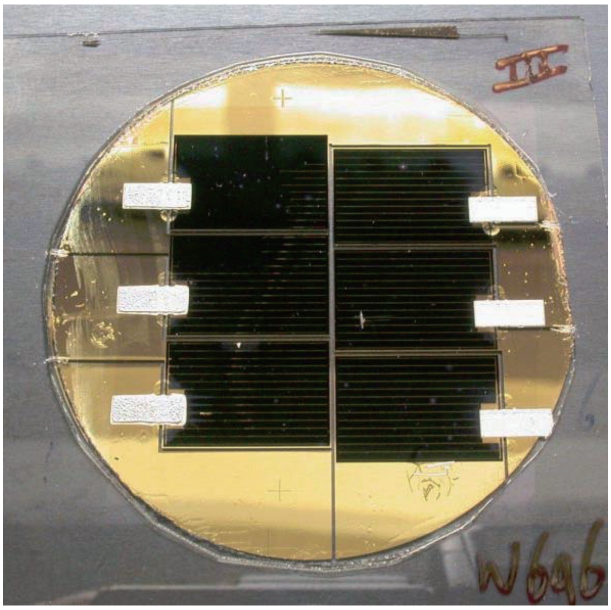

Fig. 7: Photograph of a thin-film six cell string of GaAs single-junction cells [9]. The thickness of one solar cell is less then 5 µm in this case.

Figure 7 shows an example of a solar cell string manufactured at the Radboud University in Nijmegen [9]. 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 reducing costs even further.

Another interesting approach is the inverted metamorphic solar cell [10]. A 3J solar cell is here grown upside down on a Ge 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 the those in the current 3J cell structure. Since now the bottom cell has a higher band gap of 1.0 eV higher efficiencies of about 33-34 % should be in reach 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 8). Also in this approach it might be possible to reuse the substrate.

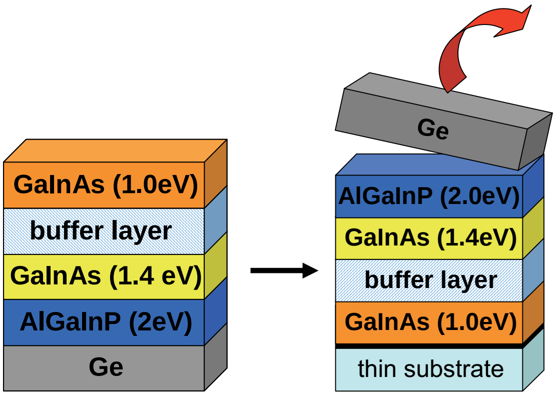

Fig. 8: Inverted metamorphic 3J solar cell. The cell is grown upside down on a Ge substrate which is removed in a later step.

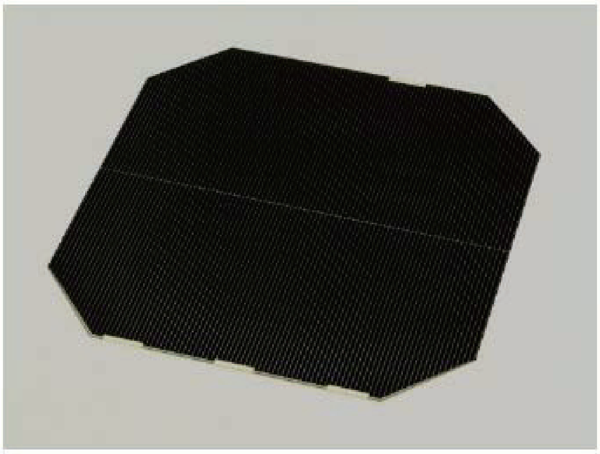

Fig. 9: Large area triple-junction space solar cell (8cm x 8cm with cropped corners) [8].

Finally, 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).

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 close to its practical efficiency limit of about 30 %. For future improvements in terms of efficiency new concepts have to be investigated. ESA is currently following both, lattice-matched approaches with the 4J cell as a long-term target and the lattice-mismatched approach in conventional and inverted configuration. Additional cost reductions are expected from a reduced cell thickness which would increase the power/mass ratio. Various approaches to obtain thin solar cells are under investigation. Going to larger solar cell areas seem to be an option for the future by which integration costs could be reduced.

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