3-6 JUNCTION PHOTOVOLTAIC CELLS FOR SPACE AND TERRESTRIAL CONCENTRATOR APPLICATIONS

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ABSTRACT

Multi-junction solar cells made from III-V compound semiconductors are the highest efficient photovoltaic devices today. Different solar cell structures have been developed for space as well as terrestrial concentrator applications in a close collaboration between the Fraunhofer ISE and RWE-SSP in Germany.

Efficiencies up to 29.1 % (AM0) have been recently achieved for a 30.2 cm^2 GaInP/GaInAs/Ge device at RWE-SSP. Triple-junction solar cells with remaining factors up to 88 % after irradiation with 1 MeV electrons at a fluence of 10^{15} cm^{-2} have been demonstrated at Fraunhofer ISE. Multi-junction solar cells with 5 and even 6 junctions for even higher radiation hardness are under development. On the other hand lattice mismatched triple-junction solar cells are an excellent solution for terrestrial concentrator applications. Efficiencies up to 35.2 % at a concentration ratio of 443-637 (AM1.5d, low AOD) have been obtained.

INTRODUCTION

Today, GaInP/GaInAs/Ge triple-junction solar cells are widely used for powering satellites in space. Efficiencies have been dramatically improved in recent years and peak values up to 30.5 % under AM0 [1,2] and above 37 % under concentration [1,3] were published. In Germany 3-junction solar cells have been developed in a close collaboration between the Fraunhofer Institute for Solar Energy Systems (ISE) and the company RWE-SSP. AM0 efficiencies have reached 29.1 % for a 30.2 cm^2 GaInP/GaInAs/Ge triple-junction solar cell (see Fig. 1) at RWE-SSP.

Even with these excellent results the performance can be further improved in the future. Different concepts are investigated, depending on the specific application of the solar cell. The roadmap for the development of space solar cells in Europe includes 5 and 6-junction devices optimized for high radiation hardness and end-of-life efficiency (see Fig. 2). This work is funded by the European Space Agency (ESA-ESTEC) and the German Ministry of Education and Science (German Airospace center). Cell structures are also developed on 30 – 70 µm thin and therefore, lightweight Ge substrates.

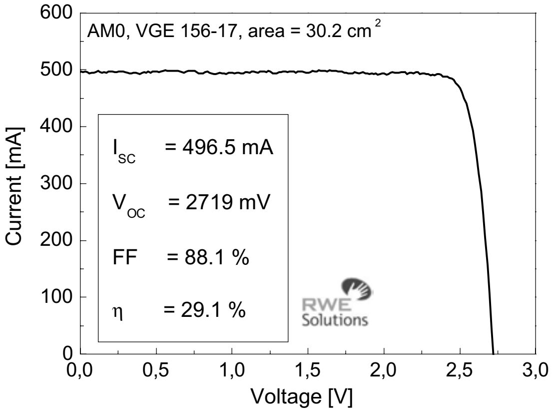

Fig. 1: Light I-V characteristics of a 30.2 cm^2 GaInP/GaInAs/Ge triple-junction solar cell (RWE 3G – 28 % class) grown and characterized by RWE-SSP.

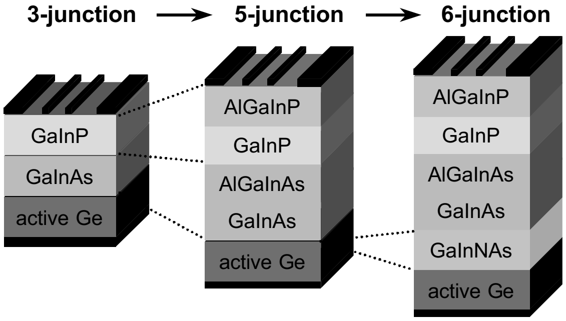

Fig. 2: European roadmap for the development of 3, 5 and 6-junction solar cells for space applications.

Besides the continuous interest in III-V multi-junction solar cells for space applications, the largest potential market for these devices is certainly terrestrial. Several high-concentration photovoltaic systems using III-V multi-junction solar cells are now in a prototype state, aiming for a market introduction in the near future. Outdoor module efficiencies in the range of 28 % are necessary for these systems to meet the targets for lowering photovoltaic power generation costs compared to flat-plate Si. The prerequisite for such high system efficiencies are III-V

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multi-junction solar cells with η > 35 % under concentrated sunlight.

The FLATCON® concentrator module (see Fig. 3) developed at Fraunhofer ISE currently uses metamorphic GaInP/GaInAs dual-junction solar cells with an efficiency of 30 % at a concentration ratio of 500 [4,5]. Several thousand cells, 2 mm in diameter, have been produced. The characterization of such large quantities of solar cells under concentrated sunlight demands for new measurement equipment. An automated IV mapper was developed in collaboration with the company AESCUSOFT. The cells are measured at a concentration ratio equivalent to 200 suns. Results will be presented in this paper.

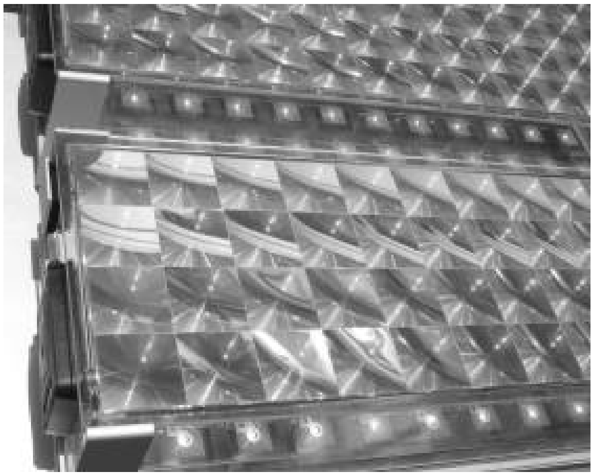

Fig. 3: Picture of a FLATCON® concentrator module with GaInP/GaInAs dual-junction solar cells developed at Fraunhofer ISE.

Recently, the metamorphic cell structure was successfully transferred to Ge substrates. An efficiency of 35.2 % was measured for a GaInP/GaInAs/Ge triple-junction solar cell at 443-637 x AM1.5d (low AOD).

Further development of concentrator solar cells for terrestrial applications is funded by the German Ministry for the Environment, Nature Conservation and Nuclear Safety and by the European Commission. Efforts are made to increase solar cell performance towards 40 % efficiency. This includes work on monolithic triple-junction solar cells as well as mechanically-stacked 3 and 4-junction devices.

The current development status at Fraunhofer ISE and future perspectives are summarized in this paper.

EXPERIMENTAL

At Fraunhofer ISE, as well as RWE-SSP, Aixtron production MOVPE reactors (Aix2600-G3) with a 24x2-inch or 8-9 x 4-inch substrate configurations are used. Standard gas and metalorganic sources are AsH_3, PH_3, SiH_4, TMGa, TMIn, TMAl, DMZn, DETe, CBr_4. The solar cell structures have been grown on either 2-inch GaAs or 4-inch Ge substrates with 6° off-orientation to [111]A. Typical reactor conditions are 50 – 100 mbar, 600 – 750 °C, V/III = 20 – 50 for arsenides and 80 – 200 for phosphides.

Processing of the layer structures to space solar cells with an area between 4 – 30.2 cm^2 has been performed at RWE-SSP. Concentrator solar cells with an area of 0.032 cm^2 were grown and fabricated at Fraunhofer ISE using typical photolithographic processing. A double-layer MgF_2/TaO_x anti-reflection coating was applied to all concentrator solar cells. The grid structure is optimized for the FLATCON® module with an inhomogeneous light intensity profile.

RESULTS AND DISCUSSION

Space solar cells

The most important parameter for III-V solar cells in space is the so called end-of-life (EOL) efficiency. This is the efficiency of the solar cell after many years of high energy particle irradiation in orbit. The EOL efficiency has to meet the power requirements of the satellite. The degradation of the cell characteristics under the high energy electron and proton irradiation depends on the semiconductor material and the specific solar cell structure. InP, for example, is known to exhibit an extremely high radiation hardness [6] and has therefore, been investigated as a solar cell material for space missions with high particle densities. In a typical GaInP/GaInAs/Ge triple-junction solar cell, the radiation hardness of the device is limited by the degradation of the GaInAs middle cell. This is due to the specific properties of the GaInAs semiconductor. High energy particles lead to displacement damage and deep recombination centers reducing the minority carrier diffusion length. Different attempts have been made to minimize the sensitivity of the GaInAs subcell to this deterioration of the minority carrier diffusion length. Partially this can be achieved by varying dopant densities and profiles as well as the thickness of the active GaInAs layers. At Fraunhofer ISE a detailed simulation of the optimum triple-junction solar cell structure after irradiation with 1 MeV electrons has been performed. The result is an improvement of the remaining factor for J_{sc} from 88 % to 96 % and for the power from 81 % to 88 %. This is an excellent value for a lattice-matched GaInP/GaInAs/Ge triple-junction solar cell and more information is published in [7].

Further significant improvements in the radiation hardness of the lattice-matched GaInP/GaInAs/Ge triple-junction solar cell are unlikely. Therefore, a new solar cell structure has been proposed by Fraunhofer ISE in 2001 [8]. This is a 5-junction solar cell consisting of AlGaInP/GaInP/AlGaInAs/GaInAs/Ge [9]. In this structure the thickness of the individual subcells is significantly reduced (between 140 - 1400 nm) and consequently a low minority carrier lifetime has a comparably smaller impact on the current generation of the device. Only well-known materials are used in the 5-junction solar cell structure which is schematically shown in Fig. 2. Compared to a state-of-the-art triple-junction device, the 5-junction solar cell has a significantly higher voltage but smaller current density. Open-circuit voltages up to 5.2 Volts have already been demonstrated for a AlGaInP/GaInP/AlGaInAs/GaInAs/Ge 5J-cell under AM0 conditions [7,10].

The external quantum efficiency of a typical AlGaInP/GaInP/AlGaInAs/GaInAs/Ge 5J-cell is shown in Fig. 4. The absorption range of the first four junctions has a large overlap due to the small thickness of these subcells. One can also see that the spectral range for the Ge bottom cell is much broader compared to the other cells. Consequently, its current-generation is also about a factor of 4 higher. In the future, another 6th subcell with a bandgap energy between 0.9 – 1.1 eV can be beneficially incorporated between the GaInAs and Ge subcell to improve the BOL, as well as the EOL efficiency (see also Fig. 2). The lattice matched GaInNAs alloy is a possible candidate. Due to the lower current of the 5-junction solar cell compared to a typical 3-junction device, the requirement on the current generation of the GaInNAs subcell in a 6-junction device is reduced and seems feasible with today's material properties.

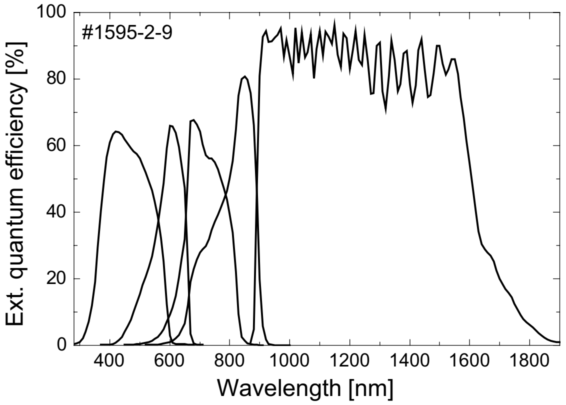

Fig. 4: External quantum efficiency of a typical AlGaInP/GaInP/AlGaInAs/GaInAs/Ge 5-junction solar cell.

A further step into the future is the development of 5- and 6-junction solar cells on ultra thin and lightweight Ge substrates. Below a thickness of 100 µm, the cells appear to be flexible. This allows the development of new flexible arrays. The lower weight can lead to reduced launch costs for the satellite. In a first attempt 3 and 5-junction solar cell structures have been lapped down to a thickness of 70 µm after the MOVPE growth (see Fig. 5). The yield for the process technology is still low, but the process seems to be feasible in the future. First triple-junction solar cells with an area of 4 cm^2 exhibit an AM0 efficiency of 23.1 %.

Fig. 5: 70 µm thin and flexible Ge wafer with solar cell structure.

Terrestrial concentrator solar cells

The application of III-V multi-junction solar cells in terrestrial concentrators has different demands. The devices are operated at high current densities of several A/cm^2. This causes specific challenges for the tunnel diode structures that are used for the series connection of the subcells. High peak tunneling current densities have to be achieved.

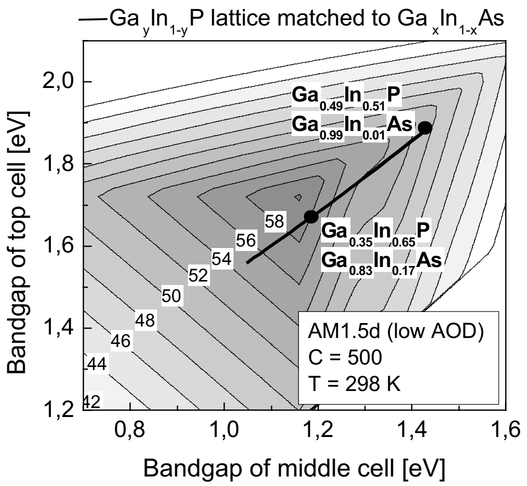

Fig. 6: Theoretical efficiency limit for series-connected 3-junction solar cells with a fixed Ge bottom cell. The AM1.5d (low AOD) spectrum at a concentration ratio of 500 was assumed. The black line indicates the bandgap energies for lattice-matching between GaInP and GaInAs.

The solar cell structure also has to be adjusted to the terrestrial spectrum, which differs significantly from conditions in space. Therefore, the optimum bandgap combination of materials is not the same. The theoretical efficiency limit for a series connected triple-junction solar cell was calculated using the program EtaOpt [11] and is shown in Fig. 6. The efficiency is plotted as a function of the bandgaps of the top and middle cell, assuming Ge as the third junction. The calculation was performed for the AM1.5d (low AOD) spectrum (C = 500 suns).

One can see that the lattice-matched combination of $Ga_{0.49}In_{0.51}P/Ga_{0.99}In_{0.01}As/Ge$ is not reaching the optimum set of bandgap energies for the concentrator application. The maximum efficiency is achieved for lower bandgap energies of both, the top and the middle cell. The black line indicates the bandgap energies of the lattice-matched ternaries $Ga_{1-y}In_yP$ and $Ga_{1-x}In_xAs$. A combination of the lattice-matched $Ga_{0.35}In_{0.65}P$ and $Ga_{0.83}In_{0.17}As$, grown on Ge with a lattice-mismatch of 1.2 % nearly reaches the optimum bandgap combination. This material combination has been intensively investigated at Fraunhofer ISE for dual-junction solar cells on GaAs substrate [8,12-16]. One of the main challenges of this structure is the large mismatch in lattice-constants between Ge or GaAs and $Ga_{0.83}In_{0.17}As$. A special buffer structure with an In gradient between 1-17 % has been developed, resulting in a carrier collection of the metamorphic materials, comparable to lattice-matched layer structures.

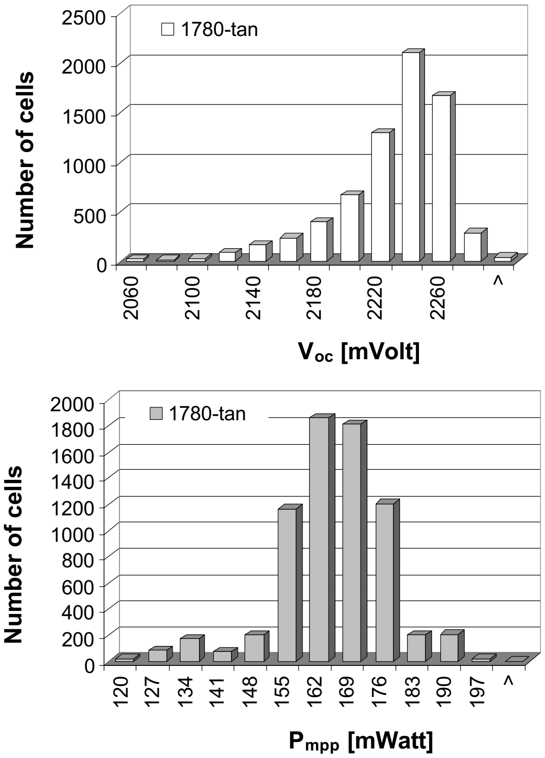

Fig. 7: Statistics of 7023 GaInP/GaInAs tandem solar cells on 2-inch GaAs. The cells 2 mm in diameter have been measured with the MAPCON IV-mapper at a concentration ratio of 200 suns.

More than 10'000 concentrator cells with a diameter of 2 mm have been processed for the incorporation in FLATCON® modules. Fig. 7 shows the statistic for the open-circuit voltage V_{oc} and the power of 7023 cells that have been measured using the MAPCON IV-mapper. This new equipment was developed in a collaboration between Fraunhofer ISE and the company AESCUSOFT. Measurements have been performed at a concentration ratio of 200 suns. The standard deviation for V_{oc} is only 1.8 %, whereas the standard deviation for J_{sc} and the power is 5.3 and 7.2 % respectively. The reason is a certain irreproducibility in the adjustment of the lamp intensity over time. This has to be solved in the future. The mapping of IV-parameters is an essential prerequisite to separate the concentrator solar cells into different performance classes.

Recently, further progress has been made to transfer the lattice-mismatched dual-junction solar cell structure to Ge. An efficiency of 35.2 % (443 – 637x AM1.5d, low AOD) has now been measured for a metamorphic 3-junction concentrator solar cell also with a diameter of 2 mm. The quantum efficiency of a lattice-matched and metamorphic triple-junction solar cell on Ge is shown in Fig. 8. One can clearly see the difference in the bandgap energies for the first and second subcell. The metamorphic triple-junction solar cell is current matched for the AM1.5d low AOD spectrum. From the spectral response, current densities of 13.8, 13.4 and 13.7 mA/cm^2 have been calculated for the top, middle and bottom cell under these spectral conditions. This shows that the Ge subcell does not generate excess current in this metamorphic 3J cell structure.

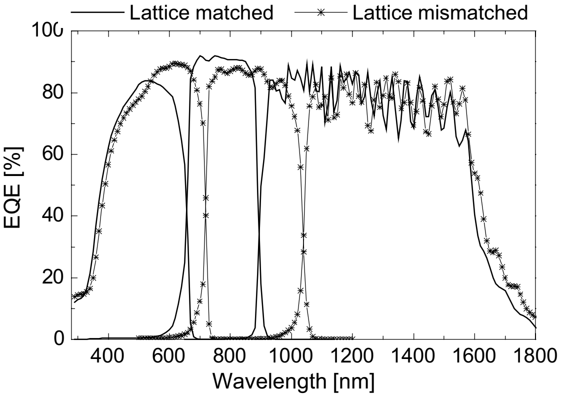

Fig. 8: External quantum efficiency of a lattice-matched and metamorphic triple-junction concentrator solar cell.

SUMMARY

Lattice-matched GaInP/GaInAs/Ge triple-junction solar cells with an European record efficiency of 29.1 % (AM0, 30.2 cm^2) were fabricated by RWE-SSP. Remaining factors of 88 % have been achieved for GaInP/GaInAs/Ge cells developed at Fraunhofer ISE. Further developments towards even more radiation hard 5- and 6-junction solar cells on 70 µm thin and flexible Ge substrates have been discussed.

Monolithic concentrator solar cells with 2 and 3 junctions based on the materials $Ga_{0.35}In_{0.65}P$ and $Ga_{0.83}In_{0.17}As$ grown lattice-mismatched on GaAs or Ge have been demonstrated. Efficiencies up to 35.2 % were achieved at C = 400 - 600 for concentrator solar cells 2 mm in diameter. Further development will focus on this metamorphic cell design with a nearly optimum theoretical efficiency.

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