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Triple-Junction III–V Based Concentrator Solar Cells: Perspectives and Challenges

This paper gives a review of the work performed in the framework of the EC-funded project FULLSPECTRUM aiming for higher photovoltaic (PV) conversion efficiencies by investigating GaInP/GaInAs/Ge *triple-junction concentrator solar cells. Lattice mismatched structures reached efficiencies beyond 35% at 600 sun concentration level. These cells are now ready to enter the terrestrial PV market. The perspectives and challenges associated with the market introduction of these cells are addressed. Specifically issues of reliability and on-wafer characterization are discussed. A new characterization tool MAPCON was developed and is presented.* [DOI: 10.1115/1.2735346]

Keywords: concentrator cells, multi-junction solar cell, PV market, III–V semiconductors, characterisation, qualification and testing

Introduction

The market for photovoltaics (PV) has been growing by more than 20–25% per annum during recent years [1]. In 2004, a growth rate of over 150% was reported for Germany [1]. These numbers are impressive and show that PV is already established in the energy market. One of the reasons for the strong market growth is the feed-in tariff first implemented in Germany and now introduced in a similar manner in several European countries like Spain and Italy. In Germany the feed-in tariff guarantees that kilowatt hours (kWhs) produced by PV are reimbursed at a fixed rate for a fixed time. However, every year the rate of reimbursement per kWh is reduced by 5% for new systems. To remain attractive for investors in the future, the costs of a PV system have to decrease at least with the same rate of 5%. There are several paths for the standard Si-based flat plate PV technology to reduce costs further, e.g., the use of thinner wafers, cost reduction in the manufacturing process by scaling effects, increase of the efficiency of solar cells in production, reduction of balance of system costs, etc. Another possibility to reduce the costs of PV produced energy might be the use of thin-film technologies like Copper Indium Diselenide (CIS) or CdTe. However, all these approaches are based on one semiconductor material. In Ref. [2] it was shown that using only one semiconductor material limits the theoretically efficiency to 31% for 1 sun illumination and 40.8% at maximum concentration, assuming a blackbody spectrum of 6000 K. This places a fundamental barrier. New technological approaches are mandatory to overcome this barrier. This is the general aim of the European funded project FULLSPECTRUM. One technological option is to use multijunction solar cells. The ultimate theoretical potential for this concept is 69.9% for 1 sun illumination and 86.8% at maximum concentration [2]. Multijunction solar cells have been realized in different semiconductor material systems. The highest reported solar cell efficiency so far is 39% (AM1.5 direct [3], 236 suns) [4]. This cell is a monolithic triple-junction solar cell consisting of the material combination GaInP/GaInAs/Ge. A typical structure of such a monolithic triple-junction cell is indicated in Fig. 1. The band gaps of the three materials decrease from the top to the bottom, thereby minimizing losses due to thermalization of hot carriers and transmission of low energy photons. Thus, the solar energy is converted intoelectricity more efficiently than in single-junction cells.

Several other companies and research institutes have reported values above 35% (for an overview see Ref. [5]). These exciting efficiency values demonstrate the viability of this approach. However, for an industrialization of this concept, further research and development have yet to be performed. In this paper the perspectives of the GaInP/GaInAs/Ge triple-junction cell for terrestrial applications together with the challenges that are accompanied by bringing this concept into an industrial process are discussed.

Development of Optimized Terrestrial III–V Triple-Junction Cells

The standard $Ga_{0.49}In_{0.51}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction cell used for space applications is optimized for extraterrestrial spectral conditions and the special demands for space. For the same material combination a maximum efficiency of 39.0% under the terrestrial AM1.5d (×236) spectrum was recently reported [4]. This success is strongly related to the high crystal perfection and electrical properties obtained for materials monolithically grown having the same lattice constants. However, the request of a lattice matched growth places a boundary condition to the band gap combinations achievable in the triple-junction cell (see Fig. 2). On the other hand, materials which are not lattice matched to each other

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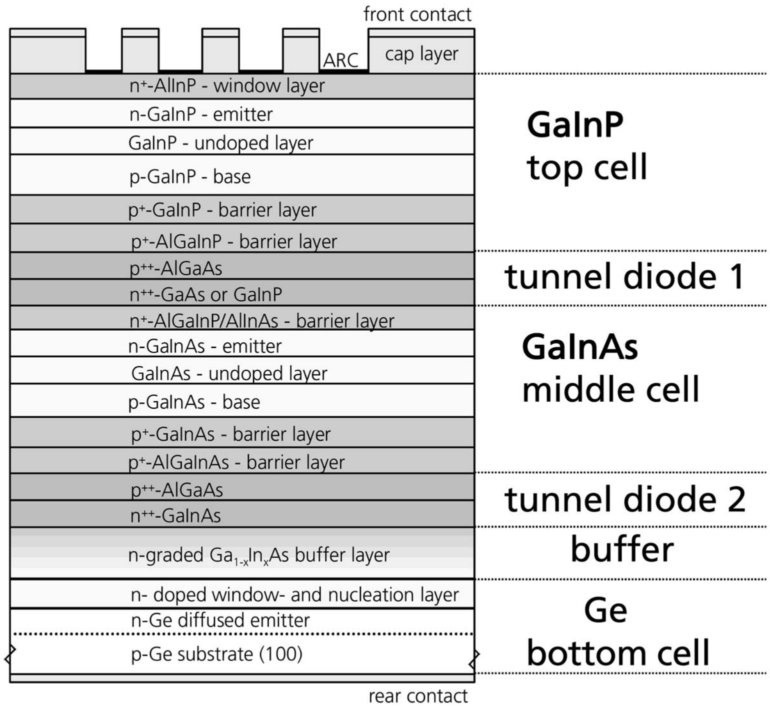

Fig. 1 Structure of a GaInP/GaInAs/Ge triple-junction solar cell. Different parts of the sun spectrum are absorbed in the different layers, i.e., the different subcells of the whole device. This results in a much more efficient use of the solar energy.

can have higher cell efficiencies as demonstrated by theoretical considerations. These theoretical considerations are based on the detailed balanced model first developed by Shockley and Queisser [6]. The only loss mechanisms considered in this model are radiative recombination. Then, the efficiency of the solar cell only depends on the cell temperature, the spectral conditions, the concentration ratio, and the band gap combination. Values obtained with this model define an upper limit for the efficiency a given structure can reach. As a rule of thumb only 75–80% of these theoretical values can be obtained in practice. Nevertheless, the potentials of different band gap combinations can be compared and the way to an optimized structure is shown. At the Fraunhofer ISE the computer code EtaOpt [7] was developed and is used to calculate theoretical efficiency limits for all kinds of cell structures.

The efficiency limit of the band gap combination of the triple-junction space structure under 500xAM1.5 direct [3] and 25°C is 51.5%. In contrast to that, the efficiency limit of a triple-junction cell with an optimized band gap combination is 60.9% under the same conditions. This value is obtained for a band gap combination of 1.73 eV for the top cell, 1.16 eV for the middle cell, and

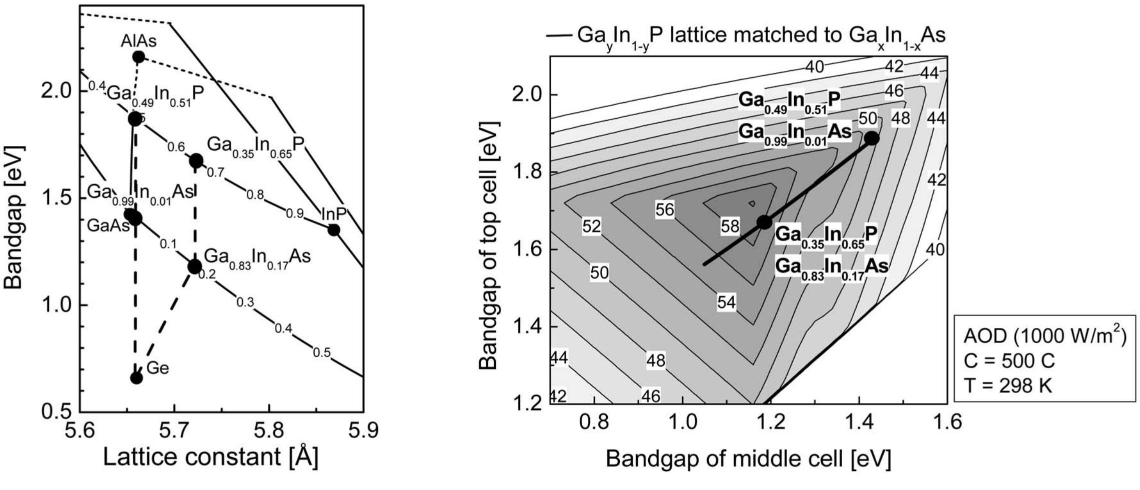

Fig. 2 (Left) The "map" for the III–V semiconductor materials. Shown are bandgaps versus lattice constants for different material combinations. The broken vertical lines indicate the two approaches which are investigated in this paper: the "lattice matched" and the "lattice mismatched" or metamorphic approach. (Right) Limiting efficiencies of monolithic triple-junction cells depending on the band gaps of the top and the middle cell. The band gap of the bottom cell was set to 0.66 eV—the band gap of germanium.

0.69 eV for the bottom cell. However, in practice, this band gap combination cannot be easily realized. In another calculation the bottom cell material is defined to be germanium which fixes the band gap of the bottom cell to 0.66 eV. Since the efficiency limit of a triple-junction cell with Ge as a bottom cell is still 60.2% this is not a strong constraint but takes into account the material which is used in real devices. In the right graph of Fig. 2, the limiting efficiencies of monolithic triple-junction cells are plotted as a function of the band gaps of the top and the middle cell assuming Ge as the bottom cell material. Compared to the lattice matched structure $Ga_{0.49}In_{0.51}P/Ga_{0.99}In_{0.01}As/Ge$ the band gaps of the top and middle cell have to be decreased to reach higher theoretical efficiencies. Starting from the $Ga_{0.49}In_{0.51}P/Ga_{0.99}In_{0.01}As/Ge$ cell this can be realized by increasing the indium content in the GaInP top cell and the GaInAs middle cell (see Fig. 2 left). As noted before, for a good material quality it is beneficial to grow the different materials lattice matched to each other. The black line in Fig. 2 indicates the band gapcombinations of a GaInP top cell and a GaInAs middle cell where both material combinations have the same lattice constant and can therefore be grown lattice matched on each other. For a GaInP/GaInAs/Ge structure with 17% indium in the middle cell, being very close to the optimum band gap combination, one calculates a limiting efficiency of 58.2%. However, it has to be considered that the lower band gaps in the upper two cells come at the expense of increasing the lattice mismatch between the epitaxial structure and the Ge substrate.

At Fraunhofer ISE both the lattice matched approach with 1% In and the lattice mismatched or metamorphic approach with 17% In content in the middle cell are investigated and optimized for terrestrial applications.

Lattice Mismatched Approach

The challenges associated with growing a mismatched structure on top of the Ge substrate include the use of buffer layers minimizing the spread of threading dislocation into the active cell regions. Threading dislocations deteriorate the material quality which in turn results in poor efficiencies. Thus, at Fraunhofer ISE different buffer structures were developed and analyzed. The quality of the buffer layers was verified with high-resolution x-ray diffraction and transmission electron microscopy measurements. Details of the buffer growth are published in Ref. [8]. It turned out that a step graded or linear buffer structure of GaInAs with increasing indium content works best, resulting in a carrier collection comparable to the lattice matched approach. External quantum efficiency (EQE) measurements reveal the electrical performance of the device. A comparison of EQE measurements of the lattice mismatched and the lattice matched approach is shown in Fig. 3.

The measurements shown in Fig. 3 were performed on 2×2 cm^2 test cells. The EQE of concentrator cells would be lower due to higher shading losses of the grid.

The difference in the band gap energies of the top and the middle cell can be clearly seen. Using the EQE data and the AM1.5 direct spectrum [3] one can calculate the current generation in the subcells (relative values). The results are summarized in Table 1. In the metamorphic structure an almost perfect current matching of the top and the middle cell is obtained. However, due to the lower band gaps of top and middle cell, the Ge subcell is now limiting the current of the complete device.

This is the first time that the bottom cell is limiting the performance of a triple-junction cell. In lattice matched cells the Ge subcell was only regarded as a voltage booster. No priority was given to improve the overall performance of the Ge subcell. In the case of the lattice mismatched approach it has now been demonstrated that the Ge subcell can limit the triple-junction cell performance.

The measurements under high light intensities are shown in Fig. 4. A maximum efficiency of 35.2% at a concentration ratio of 600

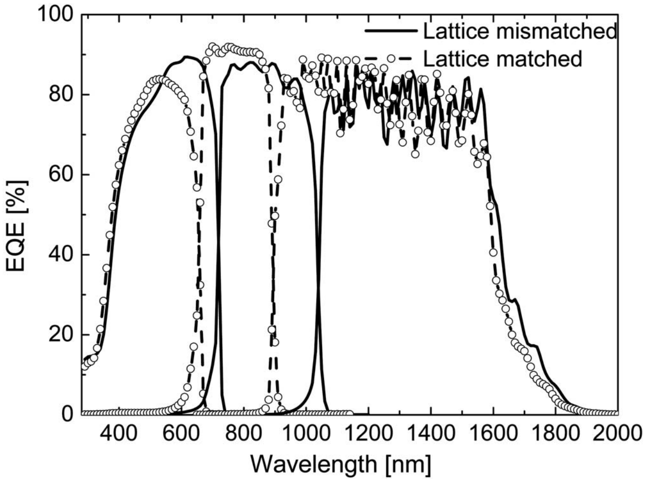

Fig. 3 **Comparison of EQE measurements for the lattice mismatched and the lattice matched GaInP/GaInAs/Ge triple-junction cell**

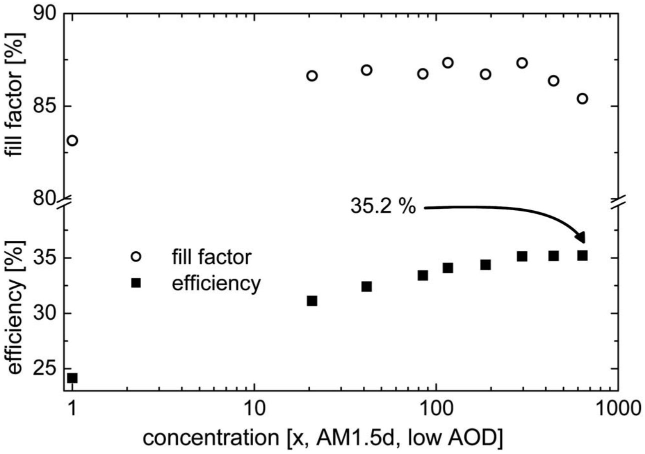

Fig. 4 **Efficiency and fill factor of the European record concentrator cell. These high efficiencies were achieved by following the lattice mismatched approach which promises a higher efficiency potential than the lattice matched approach. The maximum efficiency of 35.2% was obtained at a concentration ratio of 600 suns.**

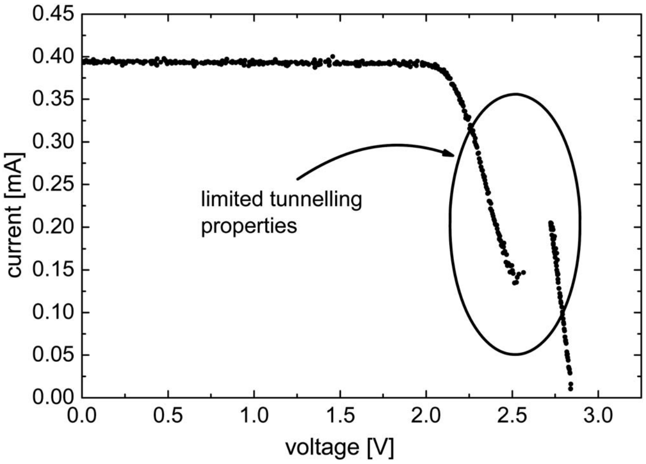

Fig. 5 ***I–V*** **characteristic of the metamorphic structure at a concentration ratio of 850 suns. The dip in the** ***I–V*** **curve indicates that the current of the cell exceeds the peak tunneling current of one of the tunnel diodes.**

Table 1 Calculated current densities of the subcells assuming the AM1.5direct spectrum [3] and the EQE shown in Fig. 3

	Lattice matched			Lattice mismatched		
	$Ga_{0.49}In_{0.51}P$	$Ga_{0.99}In_{0.01}As$	Ge	$Ga_{0.35}In_{0.65}P$	$Ga_{0.83}In_{0.17}As$	Ge
J_{SC} (mA/cm^2) AM1.5direct	12.47	15.06	20.11	16.69	16.40	14.75

suns was obtained which represents an European record for a concentrator solar cell.

However, the tunnel diodes in this cell did not work properly for concentration ratios above 600 suns. Figure 5 shows the $I-V$ characteristic of the metamorphic structure at a concentration ratio of 850 suns. The dip in the $I-V$ curve indicates that the current of the cell exceeds the peak tunneling current of one of the tunnel diodes. Following the curve from V_{OC} to I_{SC} it can be seen that as soon as the peak tunneling current is exceeded the tunnel diode behaves like a normal diode resulting in an abrupt drop in voltage.

Intensive research was performed to improve the tunnel diode structures for higher current densities. Optimized barrier layers have been identified by theoretical considerations and simulations. The purpose of these layers is to prevent dopant diffusion away from the highly doped tunnel junction and also to enhance the tunneling process itself [9]. In addition, the dependence of doping levels on the tunnel diodes was analyzed theoretically to improve the tunnel diode properties. Different test structures were grown and characterized. Furthermore, the test structures were annealed at high temperatures which should simulate the subsequent growth when producing the whole solar cell structure. Finally, improved layer structures lead to tunnel diodes with peak tunneling currents well beyond 2000 suns for both tunnel diodes in the triple-junction cell. More details of these investigations are published in Ref. [10].

Lattice Matched Approach

Due to the lattice matched GaInP/GaInAs/Ge triple-junction cell being an industrial mass product, this material combination is already better understood and developed for space applications. To meet the spectral conditions on earth, the layer thicknesses had to be adjusted. In addition, the new tunnel diode structures were implemented into the lattice matched cells.

Figure 6 shows the best results as yet obtained with the lattice matched approach at the Fraunhofer ISE. A maximum efficiency of 33.5% was achieved with this structure. This corresponds to a relative increase of 5% compared to cells optimized for space applications. Although there is still further room for optimizations the important results obtained with these cells are the high peak tunnel currents observed. As can be seen in the graph the tunnel diodes still operate at high concentration ratios of more than 1000 suns. Additional tests showed that the peak tunneling currents are even clearly higher than photocurrents corresponding to a concentration ratio of 1700 suns.

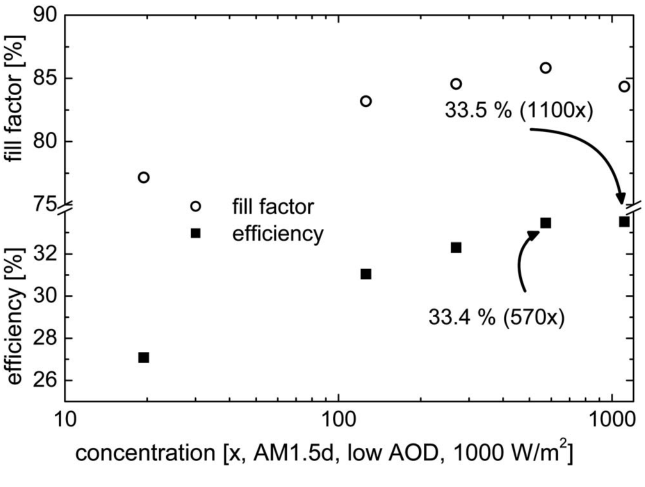

Fig. 6 Efficiency and fill factor of the best lattice matched concentrator cell. The maximum efficiency of 33.5% was obtained at a concentration ratio of over 1000 suns.

A test module in the FLATCON configuration [11] equipped with these cells reached module efficiencies of 25.9%. This is a promising result and shows that concentrator module efficiencies of up to 30% are in reach when the cell efficiencies are beyond 37%.

Reliability Tests for Concentrator Solar Cells

Another important topic for the PV concentrator technology is the reliability of the product which is one of the key issues for a successful entrance into the market. The long-term stability of concentrator cells in terrestrial high concentration environments has to be proven and qualification tests have to be established. Thereby, in fact, the system related peculiarities have to be taken into account to define suitable test methods. Nevertheless, common to all concentrator systems are high photon fluxes on the cells, high current densities, and elevated temperatures, which might cause a degradation of the device performance. In order to assess possible degradations, qualification tests yet to be defined should be inexpensive and feasible in an acceptable amount of time. Therefore, at Fraunhofer ISE [12,13] and at other institutions [14,15] accelerated aging tests have been investigated and their applicability together with their suitability have been examined. For instance, high irradiance degradation can be simulated by applying high forward currents to the cell. The equivalence of either illuminating the cell at high light intensities or applying high forward currents is given in Ref. [15]. Obviously, the latter method can be carried out much easier.

Natural degradation primarily caused by oxidation can be simulated by a damp heat test as described in Ref. [13]. There, the solar cells are stored in a 95°C/100% humidity environment easily achieved by placing them in an oven at 95°C with a water reservoir. This test was first established to qualify different window layers passivating the front side of the solar cell. Thereby, the initial cell performance was compared to the values obtained after either a long period of storage or after having performed the damp heat test. For the qualification of the window layer the acceleration factor has been found to be at least 60. However, it has to be proven that accelerated tests like the damp heat test represent conditions a concentrator solar cell will generally meet during its lifetime and whether acceleration factors can be transferred to other reliability issues concerning the cell performance.

Both the damp heat test and the forward current test have been applied to the latest generation of solar cells manufactured at Fraunhofer ISE. Even though it is believed to be a rather tough test, the cells having now optimized window layers showed no degradation after the damp heat test. Concerning degradation due to high current densities the results from the forward current test on dual-junction cells are shown in Fig. 7. There the relative $I-V$ parameters under 1 sun illumination are shown as a function of

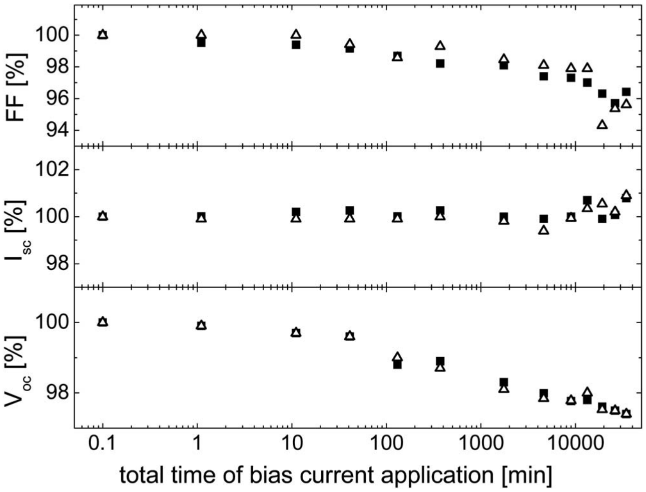

Fig. 7 Evolution of the relative *I*–*V* parameters under one sun illumination of two (triangles and squares) dual-junction solar cells aged by application of a high (0.6 A) forward-bias current

the time at which the bias current was applied. The applied current of 600 mA is equivalent to an I_{SC} at 1000 sun illumination. While the I_{SC} is unaffected by the forward-biasing, fill factor (FF) and V_{OC} are reduced by 4% and 2.5%, respectively, after 35,000 min (≈24 days). The decrease in FF and V_{OC} can be explained by an increase of the dark saturation current density J_{02} as described in Ref. [15]. However, at high concentration levels the performance of the cell is usually not affected by J_{02}. Further details of this investigation can be found in Ref. [12]. Summarizing, one can conclude that these cells will show at least no degradation related to oxidation processes or high current densities when operated at high concentration levels.

These examples demonstrate the demand for qualification tests proving the reliability of concentrator cells. Thereby, care has to be taken in defining and performing suitable tests to make sure that all failure mechanisms are properly addressed.

Industrial Production

The first GaInP/GaAs monolithic dual-junction cell was fabricated and developed for terrestrial applications by NREL [16]. However, the driving force for the further development of III–V multijunction cells was mainly the space industry. For space applications, the power to weight ratio is the important value rather than the mere material costs. This is connected with the launch costs being dependent on the mass which has to be brought into orbit. The launch costs for carrying 1 kg into space is of the order of 10 k$ [17]. In addition, the III–V multijunction cells show an excellent electron and proton radiation hardness which is essential in space. Both the high efficiencies and the better radiation hardness paved the way for the multijunction cell technology and created a market. However, this market is still small and mainly controlled by suppliers of III–V multijunction space solar cells such as Spectrolab, Emcore (both United States) and the German company RWE Space Solar Power (RWE SSP). These companies as well as a number of research institutes began to adjust the latest GaInP/GaInAs/Ge space solar cell structure for use in terrestrial concentrator applications. In PV concentrator systems, the expensive solar cell material is replaced by inexpensive optics which makes these systems cost effective and moreover cost competitive to and even outperforming Si based flat plate technologies. The market for concentrating PV is not roof-top installations but PV power plants in the range of 100 kW up to several MW. However, this is not a big challenge for the multijunction cell technology. RWE SSP, for instance, has a full load capacity of 270,000 wafers/year. Since one wafer is equivalent to 0.5 kW_P, assuming 934 cells (2 mm in diameter) with an averaged efficiency of 35% at a concentration ratio of 500 suns, RWE SSP is able to process an equivalent of over 130 MW_P/year. Similar figures have alsobeen published recently by Spectrolab [18].

Table 2 Consumption of material for a 0.5 GW, 1 GW, and 5 GW production line of a typical PV concentrator with *C*=500

	0.5 GW	1 GW	5 GW
PV concentrator area (km^2)	2.2	4.3	21.7
Number of Ge wafers (4 in.)	$1.2*10^6$	$2.4*10^6$	$1.2*10^7$
Ge material (t)	7.4	14.9	74.2
Number of MOVPE machines (12 wafers/Run)	55	110	548
AsH_3 (t)	9.1	18.2	90.7
PH_3 (t)	5.2	10.5	52.3
TMGa (t)	0.5	1.0	5.1
TMIn (t)	0.4	0.8	3.9

However, in order to make a significant contribution to the worlds' energy demand which is on the scale of TW, the annual production volume of III–V multijunction cells should at least reach the GW scale. This means not only that hundreds of new MOVPE systems will have to be installed but also that huge amounts of compound semiconductor material will be needed. Table 2 shows some numbers that have been calculated for a typical triple-junction solar cell process [19]. Please note that this calculation is based on the latest generation of metalorganic vapor phase epitaxy (MOVPE) machines with a 12×4 in. wafer capacity.

However, when discussing about production of concentrator solar cells, it is noteworthy that there doesn't exist something like "the" concentrator solar cell. There are different demands in respect to cell size and concentration ratio, and thus in contrast to the space solar cell a concentrator cell will always be a customized product because it is strongly dependent on the concentrator optics used in the respective system. For example, the Japanese company Daido Steel uses concentrator systems with Fresnel-dome lenses and homogenizers resulting in a concentration ratio of 550 suns and a typical cell size of 7×7 mm^2 [20]. Concentrix Solar, Germany, uses flat Fresnel lenses for an optical concentration of 500 suns and a circular cell with a diameter of 2 mm [11]. In the system of the Spanish company Isofoton concentration ratios of 1000 suns are also obtained using secondary optics [21]. The concentrator cells used in this system are only 1 mm in diameter. These three examples should only give an idea of the huge variety of different approaches to the concentrator concept and the system specific requirements to the solar cells. Particularly, if only a small number of cells are needed, the costs for the development of a suitable cell can be a barrier.

Investigation of Edge Cells

In order to lower the costs for concentrator multijunction solar cells and thus forcing the market entrance we investigated the use of excess material on a 100 mm wafer that is not needed by 8 ×4 cm^2 space solar cells (see Fig. 8). It has to be pointed out that the internal structure of a space solar cell is not optimized for terrestrial applications. The spectral conditions are different on earth requiring an adjustment of the cell structure for reaching highest efficiencies: layer thicknesses from the current space solar cell would have to be adjusted and/or the material compositions would have to be changed. Additional issues are related to the operation at high current densities of several A/cm^2 under concentrated light causing specific demands on the tunnel diode structures. Nevertheless, the possibility of getting the material for the concentrator solar cells for free seemed promising. Thus, different concentrator cell layouts were designed and introduced to the edge areas of wafers in the regular space solar cell production (see

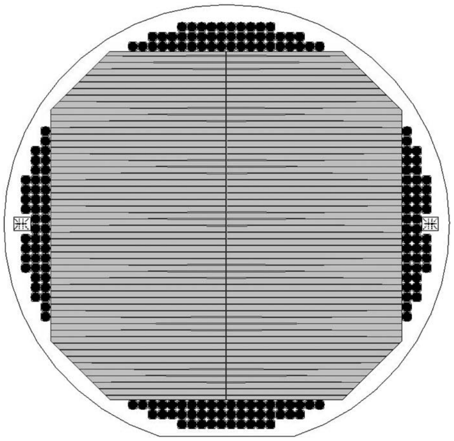

Fig. 8 A wafer with two 8×4 cm² cells with cropped corners used for space applications and 184 concentrator cells (2 mm in diameter). There is a 2 mm exclusion zone around the perimeter of the wafer, where the epitaxial structure is not homogeneous and no cells can be placed.

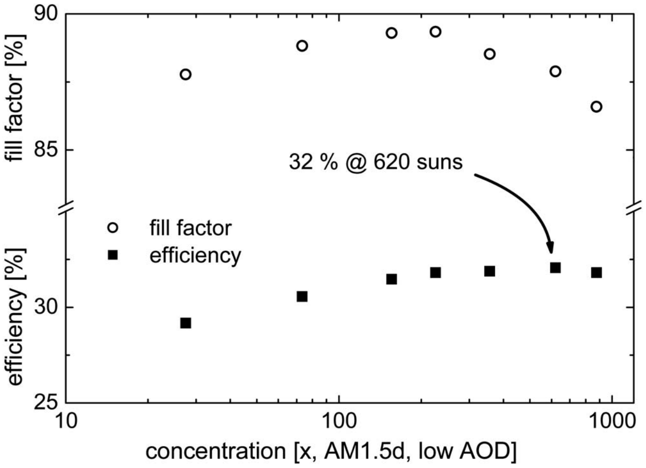

Fig. 9 Performance of a concentrator edge cell manufactured at RWE SSP. In the graph the FF (round symbols) and the efficiency (square symbols) versus concentration is given. A maximum efficiency of 32% under 620 suns is reached.

Fig. 8). In the first step, about 3000 concentrator cells with three different designs were manufactured. These cell layouts include grid finger width variations (5 μm, 10 μm) as well as linear and radial grid finger geometry. The photoactive area of all versions was 0.0314 cm^2 (cell with 2 mm in diameter).

These wafers went through the same technological process steps qualified for space solar cells. As a result, it turned out that some of the technological process steps might cause problems for concentrator cells which are related to the drastically reduced dimensions compared to space solar cells. This includes the following:

1. The definition of small structures like the 5 μm thin grid fingers;
2. Possible problems due to underetching which could cause a too high contact resistivity which is not critical for a space solar cell;
3. High intolerances to mask misalignments when superimposing the anti-reflection coating; and
4. A costly manual cutting process of the concentrator cells.

Samples of the concentrator cells were bonded and electrically characterized. The results of the measurement under concentration are shown in Fig. 9. A maximum efficiency of 32% is obtained at a concentration ratio of 620 suns. No limitation by the internal tunnel diode was found even at concentration levels of almost 1000 suns. Taking into account the nonoptimized structure of the cells for terrestrial applications, this is an excellent performance.

Based on these results and the experience from the first test production, RWE SSP performed a detailed cost analysis. There it turned out that the separation of the edge areas from the wafer and the cutting of the concentrator cells can hardly be translated into an automated process. Moreover, in spite of the structure and cell technology being free of charge, the manual cutting and further handling procedure outperforms the cost savings. Thus, as a conclusion, it is more costeffective to process wafers with solely concentrator cells on them. This will obviously increase the material costs but the cells can be automatically characterized (see next section), diced, and sorted.

Industrial Characterization of Concentrator Solar Cells on Wafer

The characterization and qualification of small concentrator solar cells in an industrial production places another challenge. A classification of the solar cells for the further manufacturing of concentrator modules is required. First of all, the characterization of concentrator cells in general and especially of multijunction solar cells is challenging and still an open issue. Concentrator cells are measured under conditions in accordance with the AM1.5 direct spectrum defined in Ref. [22] or the recently suggested AM1.5 direct spectrum with a lower and more realistic aerosol optical depth value of 0.084 at a wavelength of 500 nm.[3]. However, the level of irradiance being 500–1000 times higher than for nonconcentrator cells is typically achieved by flash light simulators. A complete $I-V$ curve measurement is carried out within the 1–10 ms flash duration. Due to the short light pulse the temperature of the cell does not change significantly during the measurement which is an issue for continuous high-intensity sun simulators. Another advantage is the good homogeneity usually observed in flash light simulators. Concentration ratios of over 1000 suns can easily be realized. A drawback of these systems is related to the problem of adjusting the spectral distribution according to the AM1.5 direct spectrum. Especially in monolithic multijunction cells efficiency values are strongly dependent on the spectral distribution of the light source which is used for the measurement [23]. This is due to the series connection of the subcells in a monolithic device. In this case the current is limited by the least performing subcell. Since the spectral distribution of a typical flash bulb is not too far away from the standard spectrum, flash simulators are up to now the best choice for characterizing concentrator solar cells [24]. However, another drawback of flash simulators are the costs. The related costs for one measurement can be easily in the range of 50 cents. This is not feasible in an

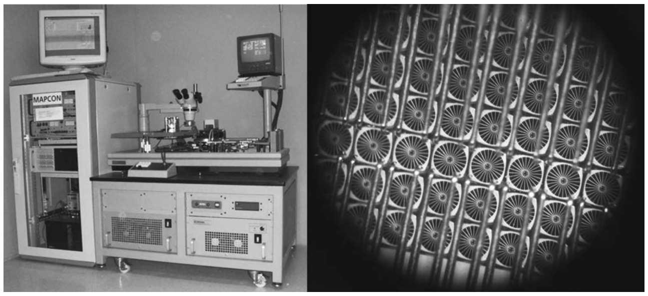

Fig. 10 (Left) IV-MAPCON setup: automatic measurement tool for on-wafer characterization of multijunction concentrator solar cells. (Right) Up to eight cells can be contacted and measured at the same time.

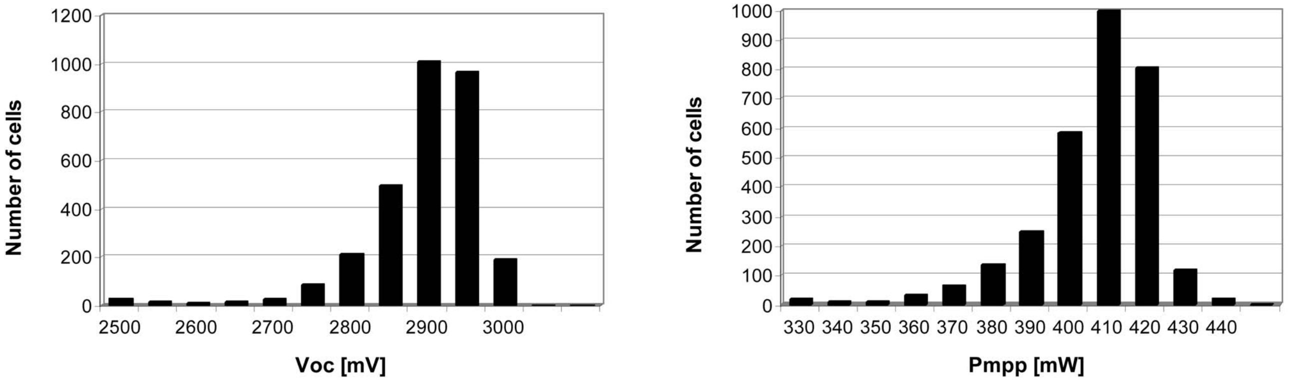

Fig. 11 Histogram of the V_{OC} and the maximum power point P_{MPP}. The results are taken from MAPCON measurements on four wafers with over 3700 concentrator cells altogether. The figures show a reasonable distribution. Please note that the *x* axis does not start from 0.

industrial production. Thus, new characterization tools have to be developed to characterize, qualify, and classify large numbers of concentrator cells on a wafer in a tolerable amount of time and at low costs. Therefore, the Fraunhofer ISE in collaboration with the company Aescusoft GmbH [25] developed a system called "MAPCON" in which up to eight cells can be contacted and measured at the same time (see Fig. 10).

The IV-MAPCON provides a solution for measurements of concentrator solar cells on 2–4 in. wafers. The system, based on a fully automated wafer probing station, can handle different wafer and cell sizes. Equipped with high concentration light sources suitable for a concentration ratio of more than 300 suns, with multipin probe cards and high accuracy multichannel measurement devices, the IV-MAPCON system is able to perform full maps of all relevant electrical parameters of small concentrator solar cells on wafers, with high speed and high resolution.

In Fig. 11 results from MAPCON measurements on four wafers with over 3700 cells are shown. Excluding the worst 5% form the statistics all P_{MPP} values are within ±7.5% around the median value which is a quite reasonable distribution and satisfies the assumption of a 95% yield in production.

The results shown demonstrate that the MAPCON system can easily handle huge amounts of solar cells. However, one has to note that this system is not considered as a tool for determining calibrated efficiencies since the spectral distribution of the light source differs strongly from standard testing conditions.

Summary

The perspectives of III–V multijunction cells for terrestrial applications have been demonstrated. High efficiency potentials and the implementation of the triple-junction cells in concentrator systems can lead to a significant cost reduction of PV. Challenges on the way to a commercial product are connected to the demand on industrial feasible characterization and classification methods. The MAPCON system developed at the Fraunhofer ISE in cooperation with the company Aescusoft GmbH gives one possible answer to the question how more than 1000 concentrator cells can be classified on one wafer cost effectively and in a tolerable amount of time.

Furthermore, the reliability, i.e., the long-term stability of the concentrator cells has to be proven. Therefore, suitable test methods have to be defined and evaluated. The stability against oxidation and high current densities has been proven for the latest generation of concentrator cells manufactured at Fraunhofer ISE.

Theoretical calculations have been performed to reveal the band gap combination which promises highest efficiencies. The metamorphic $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ triple-junction cell grown lattice mismatched on the germanium substrate features a band gap combination very close to the theoretical optimum. To obtain a good material quality in the metamorphic structure different buffer layers have been tested and evaluated. A linear or step graded buffer with increasing In content in the GaInAs layer works best and results in material with quality comparable to the lattice matched structure. Efficiencies of 35.2% and 33.5% have been achieved up to now for the lattice mismatched and the lattice matched structure, respectively. Both cell designs will be subject to further research in order to enhance material quality and to reach higher efficiencies. The industrial production of these cells will be performed by RWE SSP. With the capacities currently available increasing demands can be satisfied at least on a MW scale.

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