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High-efficiency solar cells from III-V compound semiconductors

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Today's most efficient technology for the generation of electricity from solar radiation is the use of multi-junction solar cells made of III-V compound semiconductors. Efficiencies up to 39 % have already been reported under concentrated sunlight. These solar cells have initially been developed for powering satellites in space and are now starting to explore the terrestrial energy market through the use of photovoltaic concentrator systems. This opens a huge potential market for the application of compound semiconductor materials due to the large areas that are necessary to harvest sufficient amounts of energy from the sun. Concentrator systems using III-V solar cells have shown to be ecological and could play an important role for the sustainable energy generation of the future.

Introduction A solar cell is a detector that has to convert a broad incoming spectrum into an electric current with a minimum amount of loss. The challenge is to minimize the transmission of photons through the solar cell material on the one hand and the thermalization of hot carriers on the other hand. For a solar cell that consists of only one semiconductor material the maximum energy conversion efficiency is obtained for a band gap in the range between 1.4 and 1.6 eV [1]. GaAs, therefore, has an optimum energy gap for a single semiconductor material. Higher efficiencies can only be achieved by splitting the solar spectrum into several parts. In this case a high band gap semiconductor is used to absorb the short wavelength radiation and the long wavelength part is transmitted to a second semiconductor with a lower band gap energy. In this multi-junction configuration transmission and thermalization losses of hot carriers can be reduced. This is illustrated in Fig. 1 for a solar cell that is built up from $Ga_{0.49}In_{0.51}P$ (1.9 eV), $Ga_{0.99}In_{0.01}As$ (1.4 eV) and Ge (0.7 eV).

This approach is specifically interesting if the different semiconductor materials can be subsequently grown on one substrate. In this case tunnel diodes are used to form an electrical series connection of the subcells. Such a monolithic solar cell has the advantage that the final device looks like a conventional single-junction solar cell with only one front- and back side contact. Unfortunately, the overall current in such a solar cell is limited by the lowest current generated by one of the subcells. Furthermore, the semiconductor materials have to be of high quality, which is usually achieved for material with similar lattice constant. These two boundary conditions reduce the amount of candidates for a high efficiency multi-junction solar cell. The most successful material combination today is a lattice matched solar cell that consists of three active junctions of $Ga_{0.49}In_{0.51}P$, $Ga_{0.99}In_{0.01}As$ and Ge.

The development of monolithic tandem solar cells based on GaInP and GaAs started in 1985 with the first publication and patent by J. Olson and coworkers at the National Renewable Energy Laboratory [2, 3]. The solar cells were grown by metal organic vapor phase epitaxy (MOVPE) and at this time the main problems were associated with the purity of source materials. Fig. 2 shows how the efficiency of mono-

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lithic multi-junction solar cells has since been developing. In the first half of the 1990s the solar cell structure as well as the MOVPE technology were developed to a level where space solar cell manufacturers became interested in commercializing multi-junction solar cells. As a consequence, the first satellites powered by tandem solar cells were flying in the second half of the 1990s and today GaInP/GaInAs/Ge triple-junction cells are the product of choice for most communication satellites with high power demand. The reason for this is the high efficiency and power to mass ratio that can be achieved with these solar cells, allowing to build satellites with more than 10 kW power requirement. Another important argument is the degradation of the IV-characteristics due to high energy particle irradiation in space. It has been proven that GaInP/GaInAs/Ge triple-junction cells do have advantages compared to silicon, even though materials like InP or CIS are even more radiation hard. Today, the highest efficiencies published under the AM0 space solar spectrum are in the range of 30.5 % [4, 5]. After irradiation with 1 MeV electrons at a typical fluence of 10^{15} cm^{-2}, about 15 % of the initial power are lost.

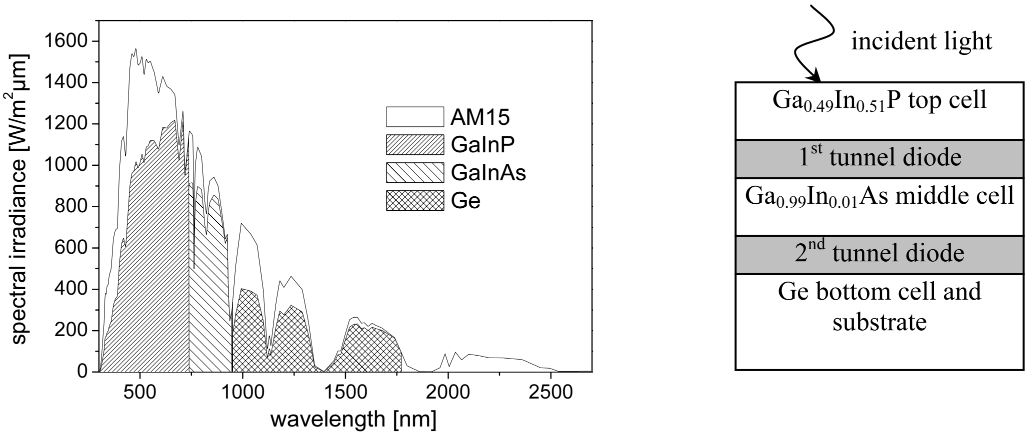

Fig. 1 Spectral irradiance of the solar AM1.5 spectrum is shown together with the parts of the spectrum that can be utilized by a GaInP/GaInAs/Ge 3-junction solar cell. The general structure of the solar cell is shown on the right.

Space solar cell manufacturers have lately realized the huge potential growth opportunity that III-V multi-junction solar cells do have if they would make a significant contribution to the terrestrial PV market. Since the beginning of the new millenium these companies as well as a number of research institutes have been using their knowledge of the latest GaInP/GaInAs/Ge space solar cells to adjust the structure for terrestrial concentrator applications. As the efficiency of a solar cell depends on the spectral conditions and increases logarithmically with the light intensity, new record efficiency values have since been obtained. The best efficiencies today are in the range of 35–39 % at concentration ratios between 200 and 600 [4, 6–9] (see Table 1 and Fig. 2).

Table 1 Highest efficiencies for monolithic GaInP/GaInAs/Ge solar cells under concentrated sunlight.

Manufacturer	technology	C	Efficiency	Ref.
Spectrolab	III-V, 3J	236	39.0	[4]
Sharp Co.	III-V, 3J	498	37.2	[7]
Fraunhofer ISE	III-V, 3J	630	35.2	[8]

Together with the improvements of the solar cell efficiency under concentrated sunlight, new companies are starting to explore the benefits of this product. Several prototype concentrator systems using III-V multi-junction solar cells have been recently realized. Fig. 3 shows an example of a 1 kW system with GaInP/GaInAs tandem solar cells developed and installed at the Fraunhofer ISE in Germany.

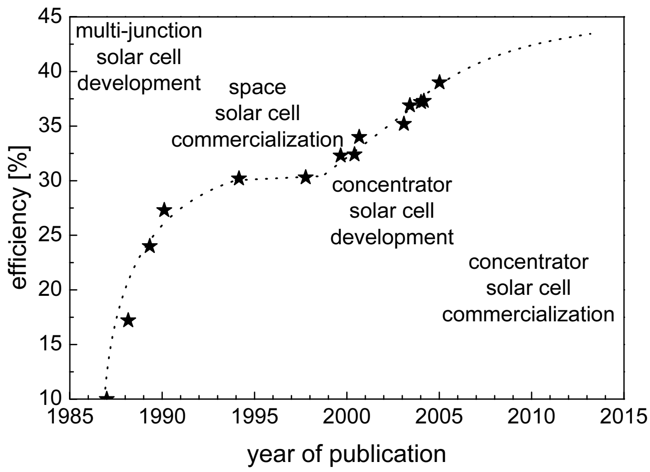

Fig. 2 History of record efficiencies published for monolithic III-V multi-junction solar cells with/without concentration (the dotted line is only a guide to the eye). The figure also shows the different phases of development and commercialization for space and terrestrial concentrator solar cells.

Fig. 3 FLATCON® concentrator system with 1 kW peak power output produced in a collaboration between the Fraunhofer ISE and ConcentriX Solar GmbH (left). GaInP/GaInAs tandem concentrator solar cells (cell area = 3.1 mm^2) on copper heat spreader (right).

Photovoltaic concentrators with III-V compound semiconductor solar cells are usually working at high concentration levels > 500 suns (1 sun defined as terrestrial AM1.5 conditions). This is due to the rather expensive substrates and processes that are used for making these solar cells. In the FLATCON® system [9], a solar cell with an area of only 3.1 mm^2 is located in the focus of a Fresnel lens. Each cell works at a current of about 200 mA and produces 0.4 Watt electrical power as well as 0.9 Watt of heat. For this reason concentrator solar cell packaging needs to be optimized towards an efficient heat dissipation, similar to high power light-emitting-diodes (see Fig. 3). Many similarities can be found between these two compound semiconductor products.

Market potential The market for space solar cells is going through certain fluctuations every couple of years, but the overall capacity of space solar cell manufacturers has not seen a significant growth over recent years. In contrary the terrestrial photovoltaic market has been growing consistently by 20–25% per annum over the past 20 years and at an impressive rate of 62 % in 2004 [10]. The amount of installed PV power per year will be passing 1 GW in 2005. Assuming a 30 % growth rate for the coming years, the annual market will be 5 GW by the year 2010. At the same time a clear tendency towards large PV installations can be observed. PV power plants up to the MW class are more frequently realized. This is an excellent opportunity for concentrator PV to enter the market, since the target for concentrating PV is not roof-top installations but photovoltaic power plants in the range of 100 kW up to several MW.
Due to the low energy density of sunlight on earth, photovoltaic energy conversion is always involving large areas. Even in the case of concentrators working at 500 suns, this means that huge amounts of compound semiconductor material will be needed to make a significant contribution. Table 1 shows some numbers that have been calculated for a typical triple-junction solar cell process. Assuming a production volume in the range of 1–5 GW of FLATCON® modules per year, hundreds of new MOVPE systems will have to be installed and this also means a continuous need for tons of metalorganic and hydride source materials as well as Ge substrates. A production volume in the GW scale still seems to be feasible and necessary to make a significant contribution to the worlds energy demand which is on the scale of TW.

Table 2 Consumption of material for a 0.5, 1 and 5 GW production line of FLATCON® PV concentrators with C = 500.

	0.5 GW	1 GW	5 GW
PV concentrator area	2.2 km^2	4.3 km^2	21.7 km^2
number of Ge wafers (4-inch)	1.2×10^6	2.4×10^6	1.2×10^7
Ge material	7.4 tons	14.9 tons	74.2 tons
number of MOVPE machines (12 wafer per Run)	55	110	548
AsH_3	9.1 tons	18.2 tons	90.7 tons
PH_3	5.2 tons	10.5 tons	52.3 tons
TMGa	0.5 tons	1.0 tons	5.1 tons
TMIn	0.4 tons	0.8 tons	3.9 tons

Space solar cell structures A monolithic multi-junction solar cell is a complex device, consisting of several pn-junctions grown on top of each other and on the same substrate material. Tunnel diodes lead to a series connection of the individual subcells. Today's most successful solar cell structure for space as well as terrestrial concentrator applications has three pn-junctions made from $Ga_{0.49}In_{0.51}P$, $Ga_{0.99}In_{0.01}As$ and Ge. Such a device consists of up to 30 individual semiconductor layers, including barrier layers and tunnel junctions, that have to be optimized for reaching ultimate performance.
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 [11] 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. 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 [12].
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 [13]. This is a 5-junction solar cell consisting of AlGaInP/GaInP/AlGaInAs/GaInAs/Ge [14]. 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 this 5-junction solar cell structure which is schematically shown in Fig. 4. 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 [12, 15].

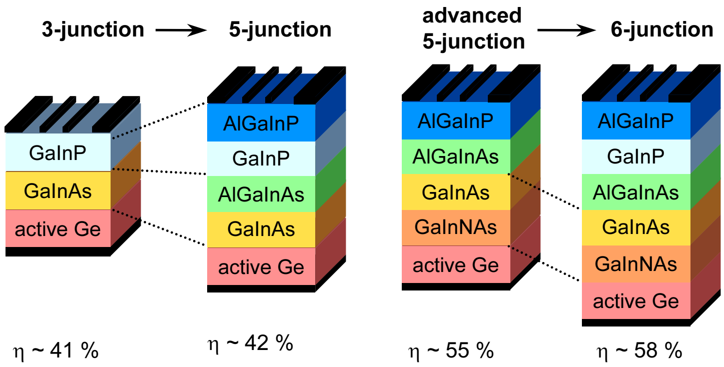

Fig. 4 Roadmap for the development of space solar cells. The given efficiencies are theoretical values calculated using the program EtaOpt [16].

The further roadmap for the development of advanced space solar cells includes new materials with a bandgap energy between 0.9–1.1 eV like the dilute nitrides GaInAsN or GaAsSbN (see Fig. 4). An incorporation of such a subcell material into a 5- or 6-junction solar cell allows efficiency improvements at begin of life, as well as after irradiation.

Terrestrial solar cell structures 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.
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 [16] and shown in Fig. 5. 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 [13, 17]. 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 [18], resulting in a carrier collection of the metamorphic materials, comparable to lattice-matched layer structures.

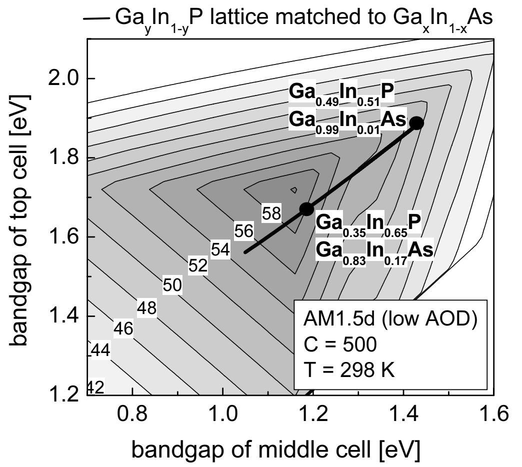

Fig. 5 Theoretical efficiency limit for series connected triple-junction solar cells with a fixed Ge bottom cell. The AM1.5d (low AOD) spectrum at a concentration ratio of 500 was assumed. The black line indicates the bandgap energies for lattice-matching between GaInP and GaInAs.

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 been measured for a metamorphic triple-junction concentrator solar cell with a diameter of 2 mm. Fig. 6 shows a comparison of the external quantum efficiencies of a lattice-matched and metamorphic triple-junction solar cell on Ge. 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, nearly equal current densities of 13.8, 13.4 and 13.7 mA/cm^2 have been calculated for the top, middle and bottom cell. This is important as the current of this series connected solar cell is always limited by the lowest current generated by one of the subcells.

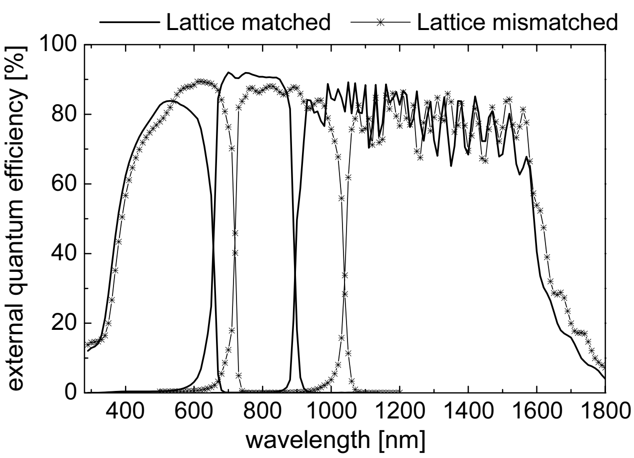

Fig. 6 External quantum efficiency of a lattice-matched and metamorphic triple-junction concentrator solar cell.

Conclusion Multi-junction solar cells from III-V compound semiconductors are today's product of choice for satellites with high power demand. The cells do have advantages due their high conversion efficiency and power to mass ratio. Also the degradation of the cell characteristics under high energy particle irradiation is comparably low. The application of this technology for terrestrial energy production in photovoltaic concentrator systems is still in its infancy. Record solar cell efficiencies are approaching 40 % under concentrated sunlight, making this technology cost competitive. This could be the starting point for a new large scale application of compound semiconductor materials. Hundreds of MOVPE machines and tons of metalorganic and hydride sources will be necessary to build up production capacities in the GW range and to make a significant contribution to the energy demand of our world economy.

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