Views

Simon P. Philipps and Andreas W. Bett*

III-V Multi-junction solar cells and concentrating photovoltaic (CPV) systems

Abstract: It has been proven that the only realistic path to practical ultra-high efficiency solar cells is the monolithic multi-junction approach, i.e., to stack pn-junctions made of different semiconductor materials on top of each other. Each sub pn-junction, i.e., sub solar cell, converts a specific part of the sun's spectrum. In this way, the energy of the sunlight photons is converted with low thermalization losses. However, large-area multi-junction solar cells are still far too expensive if applied in standard PV modules. A viable solution to solve the cost issue is to use tiny solar cells in combination with optical concentrating technology, in particular, high concentrating photovoltaics (HCPV), in which the light is concentrated over the solar cells more than 500 times. The combination of ultra-high efficient solar cells and optical concentration lead to low cost on system level and eventually to low levelized cost of electricity, today, well below 8 €cent/kWh and, in the near future, below 5 €cent/kWh. A wide variety of approaches exists for III-V multi-junction solar cells and HCPV systems. This article is intended to provide an overview about the different routes being followed.

Keywords: III-V multi-junction solar cells; concentrating photovoltaics (CPV); high efficiency.

DOI 10.1515/aot-2014-0051
Received October 7, 2014; accepted October 13, 2014; previously published online November 14, 2014

1 Introduction

Solar cells, which optimally exploit the solar spectrum, can achieve an ultra-high photovoltaic (PV) conversion efficiency. Today, it has been proven that an effective and practical path for ultra-high efficiency solar cells is the multi-junction approach, i.e., to stack sub solar cell with different materials on top of each other (Figure 1). Each subcell converts a specific part of the sun's spectrum. This reduces transmission and thermalization losses – the most important energy loss mechanism in solar cells, thus, opening the way to achieve practical efficiencies up to 50% and even more (Figure 2). However, current multi-junction solar cells are far too expensive if applied in standard PV modules. A viable solution to the cost issue is to use optical concentrating technology, in particular, high concentrating photovoltaics (HCPV), in which the light is concentrated on the solar cells at more than 500 times. Hence, the required active area of the solar cell devices is also more than 500 times lower than the area of the cheaper lenses or mirrors, thereby, decreasing the cost per unit of energy converted. The combination of ultra-high efficiency solar cells and optical concentration lead to low cost at the system level and eventually to low levelized electricity costs, today, well below 8 €cent/kWh and, in the future, below 5 €cent/kWh [1]. Moreover, by using a high concentration factor, two further advantages are obtained: (i) due to lower entropy losses, the solar cell efficiency value increases; (ii) by strongly reducing the area of the semiconductor material needed for converting the solar light, an effective answer to the problem of scarcity or limited amounts of materials in nature is found, thereby, offering a practical path to reduce the environmental impact of PV technology.

2 III-V multi-junction solar cells

Increasing the efficiency of a photovoltaic device is the aim of many research projects. A higher efficiency produces

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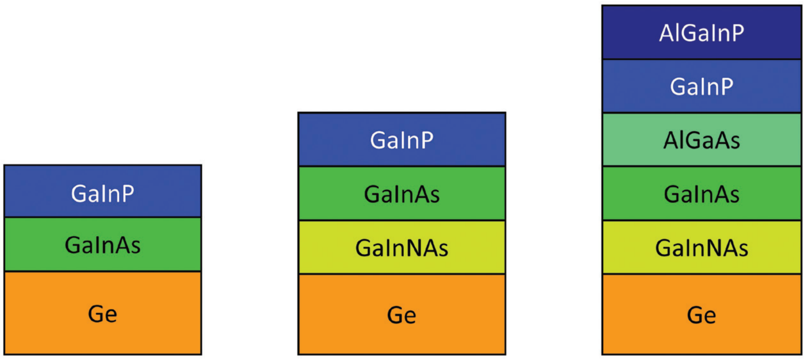


Figure 1 Sketch of examples for different multi-junction solar cells made of III-V semiconductor materials. The subcells are interconnected with tunnel diodes. Each subcell uses a different part of the solar spectrum.

the same amount of electrical power on a smaller area, i.e., less material is needed. This opens a path for reducing costs and allows for business opportunities.

The key for high efficiency is that a photovoltaic device transforms as much energy of the photons in the solar spectrum as possible into electrical energy. The part of the spectrum that can be used by a conventional single-junction solar cell is determined by the bandgap of its semiconductor material. Photons with energies below the bandgap are not absorbed and, therefore, are always lost. Photons with energy higher than the bandgap are typically well absorbed, but the excess energy beyond the bandgap is lost by thermalization processes. The idea of a multi-junction solar cell is now to stack several solar cells with increasing bandgaps on top of each other in order to (i) exploit a larger part of the solar spectrum and (ii) reduce the thermalization losses. III-V-based materials, which are composed of compounds of elements from groups III and V of the periodic table, are particularly suitable for multi-junction solar cells due to the wide range of materials and bandgaps.

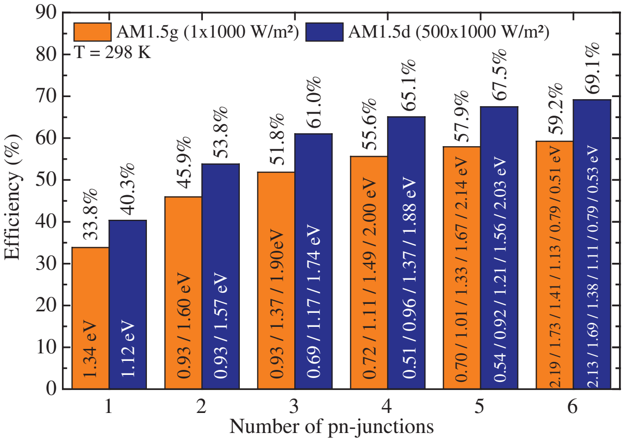


Figure 2 Dependence of the theoretical efficiency limits on the number of pn-junctions (subcells) for the reference spectrum AM1.5d under 500 times concentration (500×1000 W/m², 25°C) and the reference spectrum AM1.5g (1000 W/m², 25°C). The calculation was carried out by Fraunhofer ISE with the program etaOpt [2] according to Shockley and Queissers' detailed balance approach [3]. The model assumes ideal solar cells. A comparison with realistic solar cells indicates that – as rule of thumb – between 75% and 85% of the ideal values can be achieved in reality.

The definition of a multi-junction solar cell architecture is carried out in three steps. First, an optimal band combination is determined, e.g., based on theoretical calculations (see Figure 2). Second, suitable materials are chosen. Finally, the architecture needs to be realized. While the first two steps are relatively easy, the realization of an optimal III-V multi-junction solar cell can be challenging: as the materials are stacked directly on top of each other, their lattice constant should be similar. Otherwise, the electrical material quality needed for a solar cell cannot be sufficient due to defects and dislocations in the crystal structure. Therefore, the first technical attempt is to only use lattice-matched materials, i.e., materials with the same lattice constant. This is the case for the current industrial state-of-the-art $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction solar cell. The III-V-compound semiconductors are grown on a Ge substrate with high throughput commercial metal-organic vapor phase epitaxy (MOVPE) reactors. Tunnel diodes are implemented, which serve as a low-ohmic and highly transparent interconnect between the different subcells. As the subcells are connected in series, the voltages of the subcells sum up. The current of the total device is however determined by the minimum current of the individual subcells. In this respect, it turns out that the bandgap combination of the lattice-matched triple junction is not optimal as the Ge bottom cell receives significantly more photons than the upper two cells of

GaInP and GaAs. This results in about twice the current of the upper two subcells. Nevertheless, efficiencies of 41.6% (AM1.5d, 364 suns) have been achieved [4], and average production efficiencies are approaching 40% under concentrated light (e.g., [5–7]).

Various approaches are under investigation to increase the efficiencies further. Figure 3 gives a schematic overview of available possibilities. It can be seen as a toolbox to create high-efficiency multi-junction solar cells. The choice of substrate, the epitaxial method, the growth concepts, and eventually the post-growth processing determines the solar cell architecture and offers a wide range for different designs and solutions. In the following, we discuss some of the new concepts and technologies and provide references for further reading (Note that there are many options to combine the elements of the toolbox for III-V multi-junction solar cells. Here, only an incomplete overview can be given. For more detailed reviews, see, for example, references [8–12].).

2.1 Novel lattice-matched designs

As described above, lattice-matched growth of a triple junction on Ge substrates does not lead to an optimal split of the solar spectrum to the subcells. Theoretical calculations show that a 1.0-eV subcell placed in between the GaInAs middle cell and the Ge bottom cell of the standard lattice-matched triple-junction solar cell would lead to a nearly optimal four-junction device. Yet, the realization of such a 1.0-eV material in a lattice-matched configuration is challenging. The promising candidate GaInNAs suffers from a low minority carrier diffusion length if grown in MOVPE reactors (e.g., [13, 14]). However, a record triple-junction solar cell with an efficiency of 44.0% (AM1.5d, 942 suns) is composed of GaInP/GaAs/GaInNAs(Sb) grown on a GaAs substrate [15]. This device was grown by molecular beam epitaxy (MBE), which might also be an option for future four-junction solar cells with dilute nitrides. Obviously, for industrial-scale production, it needs to be evaluated if the production costs are competitive to MOVPE-grown devices.

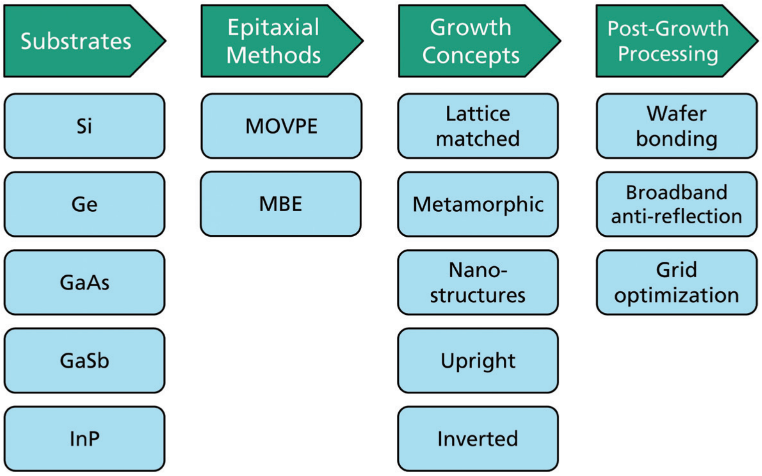
An option to realize MOVPE-grown multi-junction solar cells with a GaInNAs subcell is to move to five- or six-junction solar cells, which require lower currents for each subcell [16]. Several of such devices have already been realized (e.g., [4, 14, 17]), and the research is ongoing.

2.2 Metamorphic growth

An option that has been investigated intensively in the last years is metamorphic growth, i.e., the monolithic growth of materials with different lattice constants. In order to obtain sufficient electrical material quality for solar cell application, buffer structures are usually implemented to gradually transfer the lattice constant (e.g., [18–21]). This approach is, for example, used to grow more optimal structures on Ge substrates and to realize III-V layers on lower-cost Si substrates.

2.2.1 Upright metamorphic growth on Ge

The large excess current in the bottom cell of the lattice-matched triple-junction results from the high bandgap


Substrates

Si

Ge

GaAs

GaSb

InP

Epitaxial Methods

MOVPE

MBE

Growth Concepts

Lattice matched

Metamorphic

Nano-structures

Upright

Inverted

Post-Growth Processing

Wafer bonding

Broadband anti-reflection

Grid optimization

Figure 3 Technological tools and processes that are used to design new high-efficiency III-V multi-junction solar cells.

difference between the Ge bottom cell (0.66 eV) and the $Ga_{0.99}In_{0.01}As$ middle cell (1.41 eV). Thus, lower bandgaps for the upper two cells could increase the overall current but would also lower the voltage. Calculations show that higher theoretical efficiencies and higher energy yields can be achieved [18, 22]. Such a bandgap combination can be realized by increasing the In content in $Ga_xIn_{1-x}As$ and $Ga_yIn_{1-y}P$. However, as the lattice constant also increases, direct growth of these materials on top of the Ge bottom cell causes threading dislocations and poor material quality. The effect of threading dislocation can be reduced through the implementation of suitable buffer structures between the Ge and the GaInAs subcell, which increase the lattice constant gradually (e.g., [18, 20]). Corresponding metamorphic triple-junction solar cells have already been realized with efficiencies above 40% under concentrated sunlight [18, 19]. Theoretical calculations underline that there is still room for higher efficiencies [22].

2.2.2 Upright metamorphic growth of III-V on Si

The expensive Ge substrate in state-of-the-art III-V multi-junction solar cells makes up for a high share of the production costs. Therefore, research efforts are ongoing to grow III-V multi-junction solar cells on lower-cost Silicon substrates. As the Ge bottom cell in the lattice-matched triple-junction solar cell has a large excess current, its replacement with a higher bandgap silicon bottom cell would not decrease the overall current significantly but could enable higher voltages. A technical challenge arises from the 4.1% difference in lattice constant and the thermal mismatch between Si and GaAs. Two different approaches are being investigated to overcome this difference: wafer bonding (see below) and direct growth on the Si substrate.

For direct growth on silicon substrates, adequate buffer layers are being developed to gently transfer the lattice constant. Different strategies are investigated (for an overview, see [23]). One option is the creation of a Ge layer either directly or through the use of SiGe compounds (e.g., [24]). Another option is to realize a GaP nucleation followed by a buffer of $Ga_{1-x}In_xP$ or $GaAs_xP_{1-x}$ (e.g., [23, 25]). GaAs, GaInP, and AlGaAs solar cells on Si substrates have already been realized (e.g., [24, 26, 27]). Recently, a GaInP/GaAs dual-junction solar cell on inactive Si with a Ga(As)P buffer achieved an efficiency of 16.4% under AM1.5g [28]. Continuous efforts are necessary to improve the buffers in order to achieve efficiencies closer to the theoretical potential of III-V on Si architectures.

2.3 Inverted metamorphic growth

Efficiencies above 40% (AM1.5d) have been reached with inverted metamorphic growth (IMM) recently [7, 29–34]. In this approach, the multi-junction solar cell is grown inversely with the top cell being grown first on a lattice-matched substrate followed by the other subcells. Lift off and transfer techniques are then used to remove the substrate from the top cell after growth and to handle the thin layer structure. From a technical point of view, the IMM approach has mainly two advantages compared to upright growth. First, the growth of the buffer is postponed to later growth phases, while the upper cells can be grown lattice matched to the substrate. Thus, threading dislocations due to the transfer of the lattice constant do not affect the upper cells. Second, the bandgap of the bottom cell can be chosen as more flexible as the cell is grown epitaxially and not made of Ge. Economically, a cost benefit in production could arise if the same substrate is reused for several epitaxial runs. Yet, this might be counterbalanced by higher production costs and lower yield due to the complexity of the cell fabrication process. The possibility for flexible modules could be another benefit.

Several different designs of IMM triple-junction solar cells have been realized, which underlines the high flexibility of this approach (e.g., [7, 29, 30, 32, 35, 36]). Indeed, a record efficiency of 44.4% (302xAM1.5d) have been presented by Sharp with triple-junction solar cells [37]. Four-junction solar cells with efficiencies significantly above 40% have been reported by NREL and EMCORE [33, 34].

2.4 Wafer bonding

The technology of wafer bonding can be seen as a post-growth technology and allows combining independently grown (multi-junction) solar cell structures. This opens a much higher degree in flexibility for substrate and, thus, lattice constant choice without the need of metamorphic buffer layers. Usually, one stack is grown inversely. The cells are then, in principle, just pressed together in a bonding process followed by a lift-off process to remove the substrate. The total process is technologically challenging. Yet, promising results have already been achieved (e.g., [38–42]).

Results for wafer bonding of III-V materials on silicon substrates have been published in, e.g., [38, 39]. A wafer-bonded GaInP/GaAs//Si triple-junction solar cell was realized with an efficiency of 23.3% (AM1.5d, 24 suns) [42], and recently, this value did rise up to 27.9% (AM1.5d, 48 suns). Further research is necessary to improve the quality of the bonding interface. Moreover, the solar cell layer structure leaves room for optimization. Yet, the achieved results show the high promise of wafer bonding of III-V solar cells on silicon.

Wafer bonding is also used to create multi-junction solar cells with more than three junctions (e.g., [41, 43, 44]). Recently, a consortium of Fraunhofer ISE, Soitec, CEA-Leti, and Helmholtz Center Berlin investigated a four-junction solar cell using wafer-bonding technology for terrestrial concentrator applications. Here, the challenge is to obtain a very low ohmic resistance at the wafer-bonding interface [45]. The structure consists of a GaInP/GaAs dual-junction wafer bonded to a GaInAsP/GaInAs dual junction. A certified record efficiency of 44.7% (AM1.5d, 297 suns) has been achieved [46, 47]. An even higher value of 46.5% (AM1.5d, 324 suns) has recently been reported, but is not yet officially certified [48].

3 CPV system approaches

III-V multi-junction solar cells have rather high costs per area compared to conventional single-junction solar cells, which is due to the technical complexity and the expensive materials used. Therefore, the entry market for III-V solar cells was space applications, where cost of power per weight is the cost measure. Nowadays, III-V multi-junction solar cells are standard in space, while Si solar cells disappeared from the space market. A cost-effective use of high-efficiency multi-junction solar cells on Earth is enabled in high-concentrating photovoltaic (HCPV) systems, which use inexpensive concentrating optics like mirrors or lenses to focus the light on a small area of solar cells. Concentration factors of up to 1000 are realized. Here, the concentration factor is defined as the ratio of the optical aperture to the active cell area. Thus, the required expensive semiconductor area is significantly reduced compared to flat-plate modules. HCPV approaches had been investigated on a scientific and prototype level for a long time. Technical progress and the increasing efficiencies of III-V multi-junction solar cells have finally enabled that several cost studies showed a realistic potential for very low cost on kWh level in sunny regions. In consequence, since 2005, the HCPV market is increasing continuously [49]. The most promising application for CPV systems are solar power stations with 10 to 100 MW_p in countries with a large fraction of direct solar radiation.

A wide variety of HCPV approaches have been, and are still, investigated. Most of these can be grouped according to the concentrating optics used in central receiver and point-focus concepts (This article gives an overview about the concept and the state-of-the art of high concentrating photovoltaics. For more detailed overviews, the authors also recommend references [50–53].).

3.1 Central receiver concepts

In central receiver concepts, a relatively large concentrating optic is used to focus the sunlight onto a PV receiver (like a small PV module) made of densely packed III-V

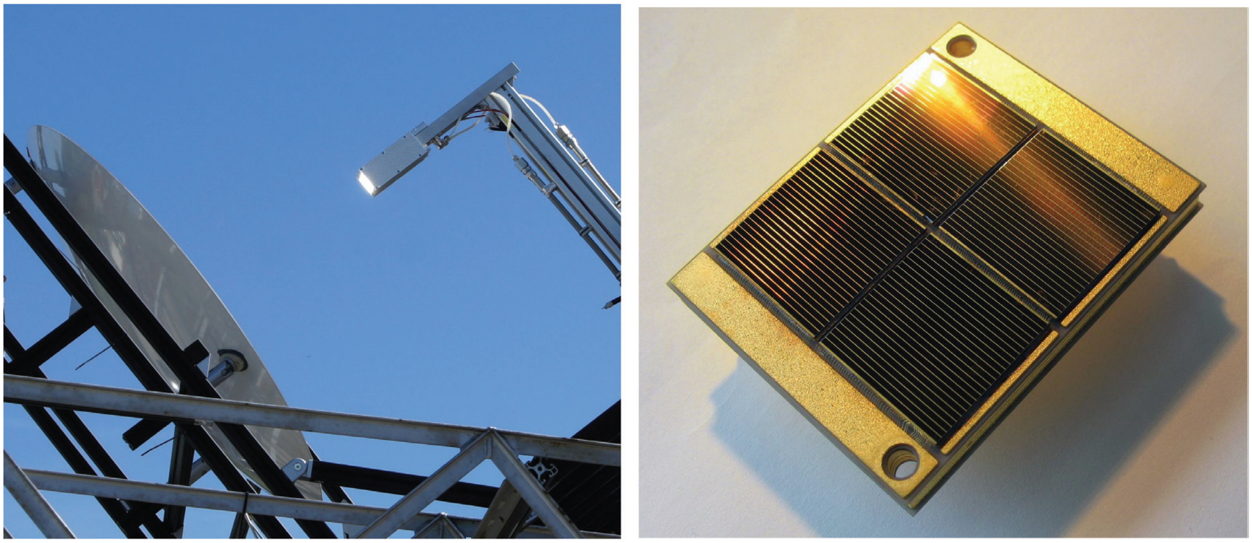


Figure 4 Example of a paraboloid and a central receiver test setup as installed at the Fraunhofer ISE [54]. Here, the diameter of the concentrating mirror is 1.2 m, while the receiver has an area of 4.5×4.5 cm^2 consisting of four single-junction monolithically interconnected modules (MIMs) [55].

multi-junction solar cells. Figure 4 shows a photo of a test setup for such an approach using, here, a paraboloid as concentrating optics and a central receiver. In real systems, the concentrating optics has diameters larger than 10 m, and the photovoltaic receiver has an area of several 100 cm^2. As the sunlight is focused by a factor of up to 1000 onto the central receiver of several 100 cm^2 (i.e., with power densities of 1.000.000 W/m^2), the receiver needs to be actively cooled to avoid burning. Typically, a water-cooling system is applied.

Active cooling can be a drawback in desert areas. However, in areas where water is not scarce, the generated thermal energy can be utilized in a properly designed system (Figure 5). These systems are called CPVT (CPV and thermal) systems. An example for a commercial CPVT installation is in Yavne (Israel) from Zenith Solar [57]. The potential of the CPVT approach has been investigated theoretically in reference [56]. Overall system efficiencies of 75% are possible. In an experimental outdoor test setup developed at Fraunhofer ISE (see Figure 4), a total system efficiency of 63% with an electrical efficiency of 14% and a thermal efficiency of 50% was achieved [49]. This prototype receiver already underlines the high efficiency potential of CPVT.

Even larger central receiver concepts are solar towers, which are well-known in CSP technology. The sunlight is focused by a heliostat field onto a centralized area in a tower. This means PV receivers with a size of several square meters, actively cooled, and suitable for light intensities of 1 MW/m^2 are needed [58]. Obviously, this approach is technically very challenging. However, first pilot installations, with lower concentration ratios, have already been realized by Solar Systems (now Silex), Australia [59].

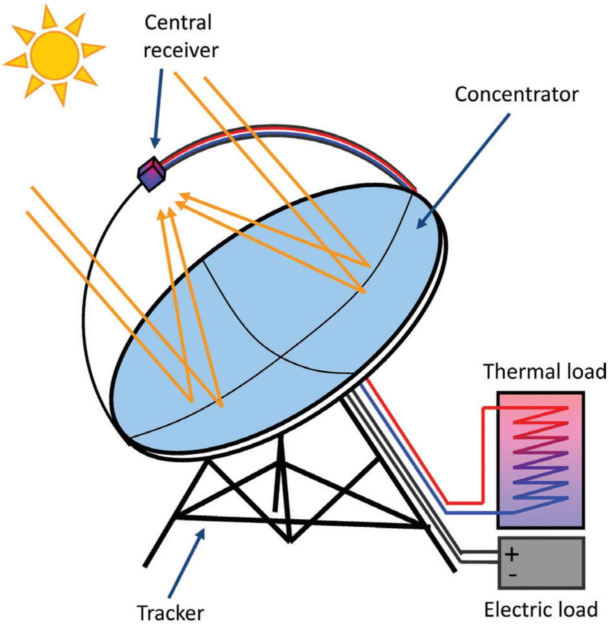


Figure 5 Schematic drawing of a concentrator photovoltaic and thermal system [56].

3.2 Concepts with point focus

In contrast to the central receiver designs, concepts named with point focus use much smaller concentrating optics to focus the sunlight onto tiny solar cells. Owing to the small-sized solar cells, typically less than 1 cm^2, this concept does not need active cooling but rely on standard passive cooling concepts in PV. One of the HCPV concepts available on the market is the FLATCON® concentrator module developed at Fraunhofer ISE [60] and today commercialized by Soitec Solar. The concentrator module uses a Fresnel lens to concentrate the sunlight by a factor of 500 on a small solar cell, which is placed on a metal plate to spread the local heat and enable passive cooling (Figure 6, left). The modules are positioned on a two-axis tracker, which assures that the solar cells are in the focus of the lenses throughout the day (Figure 6, right). Fraunhofer ISE recently demonstrated a CPV module efficiency of 36.7% at Concentrator Standard Test Conditions (CSTC) [61].

Soitec Solar commercializes this technology named as CONCENTRIX™ and has already implemented several large CPV power plants, e.g., in South Africa (Figure 7). The high efficiency of the III-V multi-junction solar cells used in this concept is one of the key aspects that lead to high operating AC efficiencies of around 25–29% for the CPV system.

The majority of today's commercial CPV systems use the described point-focus principles. This is mainly due to the easier system assembly and to the avoidance of cooling water. Several power plants with a size of more than 1 MW each using point-focus systems have already been installed worldwide.

4 Conclusions

With efficiencies up to 46.5% (324xAM1.5d), III-V-based multi-junction solar cells have achieved the highest conversion efficiency of sunlight into electricity and outperform all other materials. By implementing these devices into concentrating photovoltaic modules and systems, high efficiencies and low levelized cost of electricity can be achieved in areas with a high share of direct sunlight (Figure 8). The key

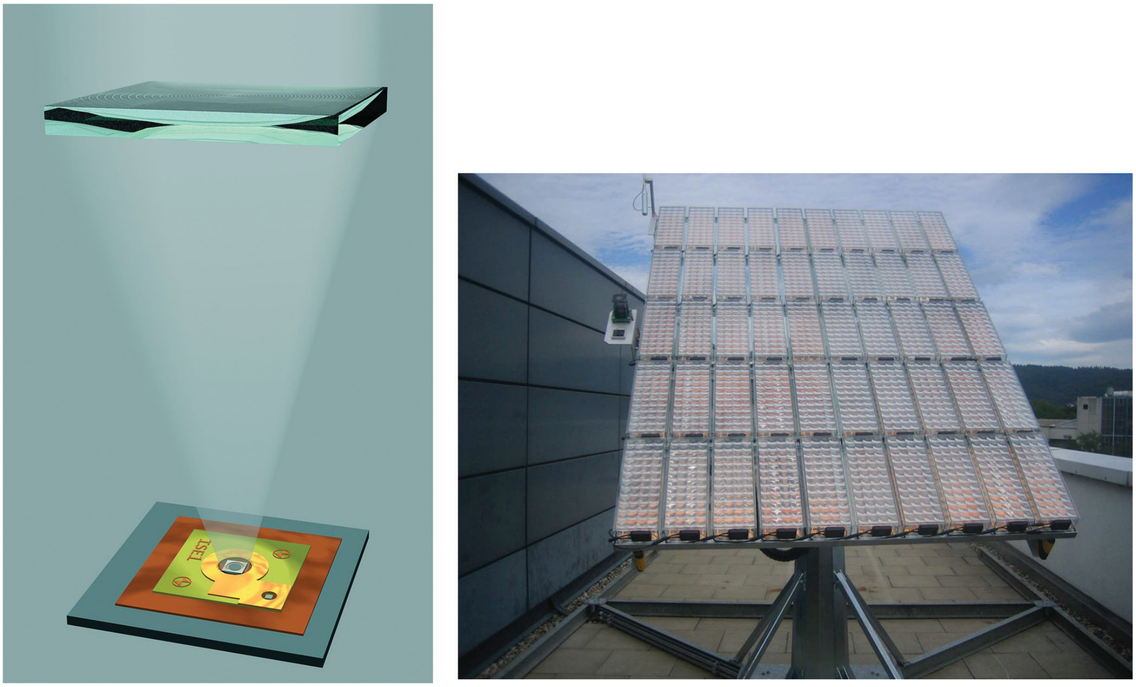


Figure 6 Example of a CPV system using Fresnel lenses to concentrate the sunlight: FLATCON® concept originally developed at Fraunhofer ISE.

Figure 7 CPV power plant of Soitec Solar in Touwsrivier, South Africa. A capacity of 44 MW_p is grid connected (Picture: © Soitec).

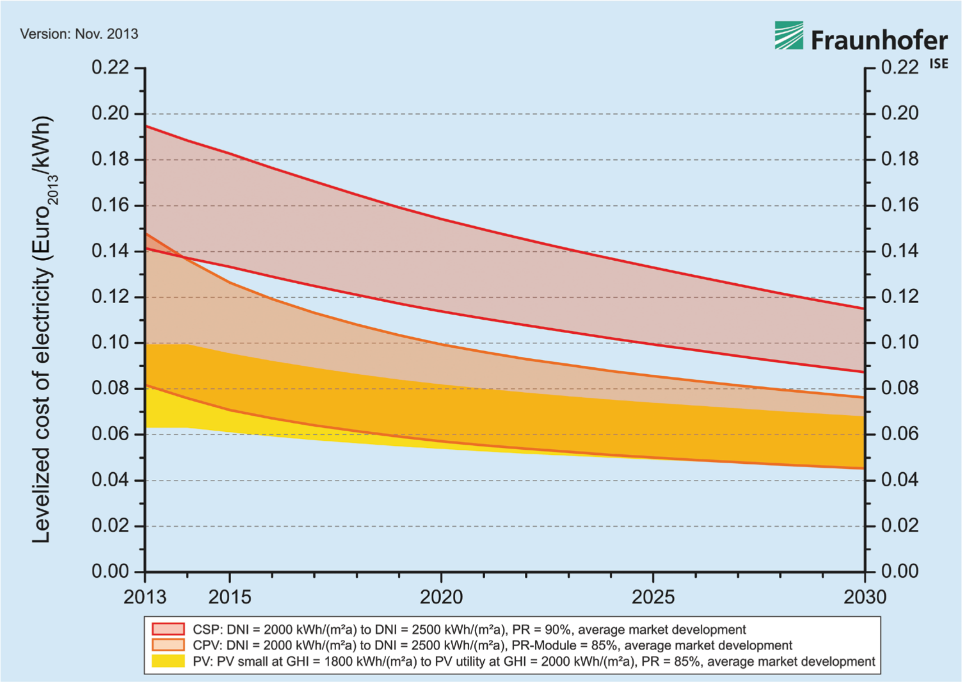


Figure 8 Learning curve-based prediction of levelized cost of electricity (LCOE) of various solar technologies at locations with high direct solar irradiation underline the low-cost potential of CPV [1].

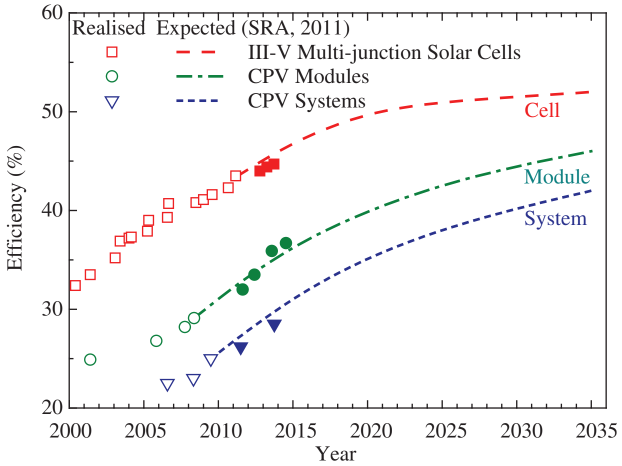


Figure 9 Development of record efficiencies of III-V multi-junction solar cells and CPV modules under concentrated light (cells: x*AM1.5d; modules: outdoor measurements). Progress in top-of-the-line CPV system efficiencies is also indicated (AM1.5d lab records according to Green et al., Solar Cell Efficiency Tables from 1993 [62] to 2014 [47]; CPV module and system efficiencies collected from various publications). The trend lines show expected efficiencies from the European Photovoltaics Technology Platform in 2011 [63]. Recent efficiency values (full symbols) follow the trend very well.

driver for low cost is the efficiency. Figure 9 shows achieved practical efficiencies of III-V multi-junction solar cells, HCPV modules, as well as HCPV systems. A continuous increase has been achieved, and projections – given in the Strategic Research Agenda (SRA) of the European Photovoltaic Technology Platform in 2011 – indicate that there is still a large room for improved practical performances. It is also noteworthy that a comparably large gap of more than $10\%_{\mathrm{abs.}}$ exists between cell and module efficiencies, which indicates significant losses in the module that must be reduced. New designs as well as new tools and fabrication processes must be developed to fulfill the efficiency projections. Several of these have been outlined in this paper.

Acknowledgments: The authors wish to thank all members of the department *III-V – Epitaxy and Solar Cells* at Fraunhofer ISE.

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