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# III-V MULTI-JUNCTION SOLAR CELLS:
# MARKET, TECHNOLOGICAL STATUS AND RESEARCH TRENDS

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## ABSTRACT

III-V multi-junction solar cells have become standard in space and in terrestrial concentrator systems. These devices reach the highest efficiencies of any photovoltaic technology so far. This is enabled by stacking solar cells of several III-V compound semiconductors, which absorb different parts of the solar spectrum. The current landmark for III-V multi-junction solar cells is the $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction, which only contains lattice-matched layers. This MOVPE-grown device is available from different suppliers in large quantities with efficiencies around 40% under concentrated sunlight. A record efficiency of 41.6% has also been achieved. Due to the mature development status of this device new concepts are being investigated to increase the efficiencies further. A toolbox of new ideas and methods is available such as metamorphic and/or inverted growth, wafer-bonding, different substrates, nanostructures, MBE growth and new materials. These have been used and combined intensively in recent years to develop and realize new structures of III-V multi-junction solar cells. The aim of this paper is to give an introductory overview about the status and the research trends in III-V multi-junction solar cells.

## 1. INTRODUCTION

III-V solar cells are composed of compounds of elements from groups III and V of the periodic table. In the corresponding multi-junction devices several solar cells made of different III-V semiconductors are stacked with decreasing bandgaps from top to bottom. This reduces thermalisation losses as photons are mostly absorbed in layers with a bandgap close to the photon's energy. Moreover, transmission losses are reduced as the absorption range of the multi-junction solar cell is usually wider than for single-junction devices. Finally the use of direct III-V semiconductors facilitates a high absorption of light even in comparably thin layers. These are the main reasons, why III-V multi-junction solar cells reach the highest efficiencies of any photovoltaic technology.

Figure 1 shows the development of efficiencies of III-V multi-junction solar cells under concentrated sunlight. Record efficiencies of international laboratory cells show an impressive increase from 32.6% in 1993 [1] to the current record value of 44.0% [2]. Lab record values of laboratory cells produced at Fraunhofer ISE are also indicated. In recent years an increasing number of companies offer III-V multi-junction solar cells for concentrator applications in large quantities [3]. As shown in the graph average commercial cell efficiencies are only about $10\%_{\text{relative}}$ lower than the record values.

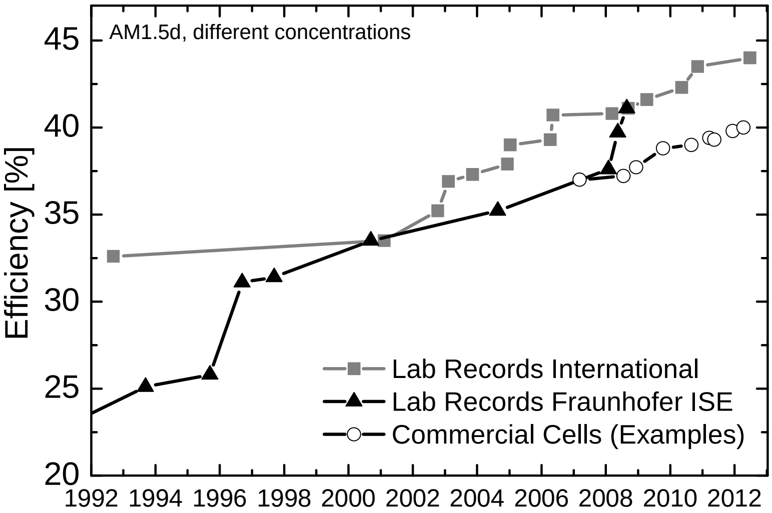

**Figure 1**: Development of III-V multi-junction solar cell efficiencies under concentrated light (x*AM1.5d). Records of laboratory cells worldwide and from Fraunhofer ISE are shown. Examples for typical commercial cell efficiencies are also indicated. (Int. Lab Records according to Green et al., Solar Cell Efficiency Tables from 1993 [1] to 2013 [2]).

## 2. MARKET

The cost competiveness of an energy producing technology is often rated by the levelized cost of energy (LCOE), which is defined as the total cost of a the system divided by its lifetime energy production. For PV high efficiencies are essential for lowering the LCOE as more energy can be produced from the same installation area [4]. However, this only holds true if increased system costs do not outweigh the benefit of higher energy production. III-V multi-junction solar cells are essentially more expensive than conventional, e.g. Silicon-based solar cell technologies on the same cell area. The main cost driver is the substrate used: The price of typical GaAs or Ge wafers is about a hundredfold higher than for a Silicon wafer. Thus, even if their efficiency is about twice as high, substrate-based III-V multi-junction solar cells are currently too expensive for the use in flat-plate modules on Earth.

However, large-area III-V multi-junction solar cells are nowadays standard in space applications as the major cost measure there are €/kg rather than €/$W_p$ [5]. This is due to the high launch costs and the importance of spacecraft attitude control [6]. Besides cost aspects III-V multi-junction solar cells are also particularly suitable for the need in space due to their radiation hardness, small temperature coefficients, high reliability and the combination of high voltage and low currents [7]. The development of III-V multi-junction solar cells has been driven by the comparably stable space market (see Figure 2, left) for a long time.

In recent years III-V multi-junction solar cells have also entered the terrestrial PV market – not in flat-plate modules but in concentrating photovoltaic (CPV) systems. These use cost-efficient concentrating optics to reduce the expensive cell area, which allows competitive LCOE. Lately, many companies have implemented this idea with a variety of CPV concepts and an increasing number of installations worldwide. The right graph in Figure 2 shows the development of the newly installed CPV capacity per year and the cell technology used. Since 2009 III-V multi-junction solar cells have been standard in CPV systems.

Another approach, which could reduce the cost of III-V solar cells is to re-use the expensive semiconductor substrate after carrying out a liftoff of the solar cell [8, 9]. The resulting thin-film solar cells have high efficiencies and can be used in flexible modules. As of late this approach is followed commercially and is seen as a way to enable the use of III-V solar cells in flat-plate modules in building-integrated as well as rooftop applications in the near future [10].

It should be noted that III-V solar cells are also used in several niche applications such as laser power converters (e.g. [11-14]) and thermophotovoltaics (TPV) (e.g. [15, 16]). More details can be found in the mentioned references.

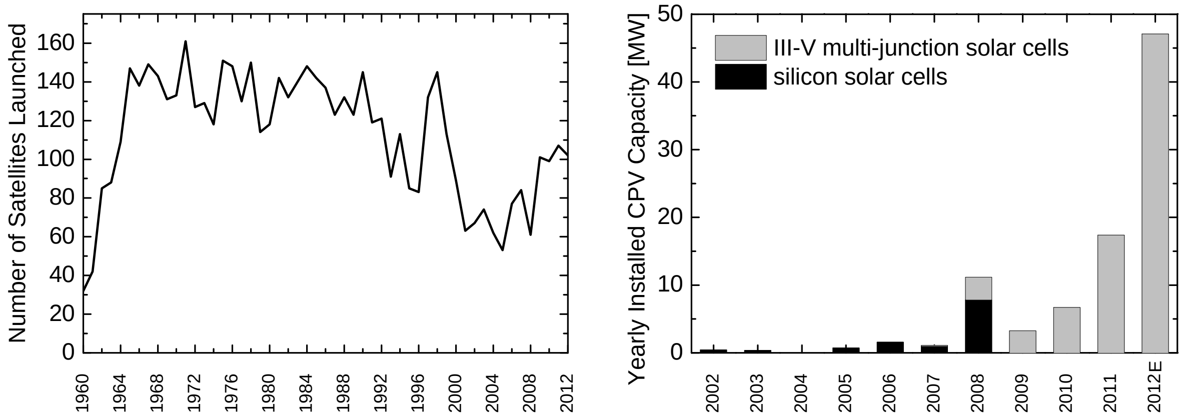

**Figure 2**: Left: Number of yearly launched satellites (Source of data: [17] for 1960-2008; www.satelliteonthenet.co.uk for 2009-2012). Right: Yearly installed capacity of CPV systems with indication of the solar cells used. III-V multi-junction solar cells have become standard in CPV systems. (Graphic adapted from Wiesenfarth et al. [18]).

## 3. CURRENT RESEARCH TRENDS[1]

The state-of-the-art approach in space and terrestrial concentrator systems is a lattice-matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction solar cell. The device is grown with high throughput in commercial metal-organic vapor phase epitaxy (MOVPE) reactors. All semiconductors in this structure have about the same lattice constant as the Ge substrate, which facilitates crystal growth in high material quality. However, its bandgap combination is not optimal as the bottom cell receives significantly more light than the upper two cells resulting in about twice the current of the upper two subcells. Nevertheless, a record efficiency of 41.6% (AM1.5d, 364 suns) has been achieved [20] and average production efficiencies are as well approaching the 40%-mark (e.g. [21-23]).

Various approaches are under investigation to increase the efficiencies further. Figure 3 exemplarily presents different cell architectures, which are under investigation at Fraunhofer ISE. A detailed discussion of each cell structure is out of scope of this paper. However, some of the following new concepts and technologies are used:

- *Metamorphic growth* of monolithic materials with different lattice constant. For sufficient material quality buffer structures are usually implemented to gradually transfer the lattice constant (e.g. [24, 25]).
- *Inverted growth* with the top cell being grown on a substrate first followed by the other subcells. This allows growing the upper cells lattice-matched to a substrate as buffers are

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[1] Parts of this section are based on reference [19].

postponed to later growth phases hence ensuring high material quality in metamorphic structures (e.g. [23, 26-31, 32 ]).

- *Wafer-bonding* is used to stack separately grown (multi-junction) solar cells with different lattice constants, which avoids buffer structures (e.g. [33-37]).
- *Other substrates* than the usual Ge substrate for lower costs (e.g. Silicon) and/or higher efficiencies (e.g. InP [38, 39]).
- *Nanostructures* such as quantum wells (e.g. [40-43]) or quantum dots (e.g. [44, 45]) are included into subcells to increase their current. Another recent approach is the growth of III-V materials in nanowires in order to reduce material consumption and to avoid dislocations especially if combined with metamorphic growth [46, 47]. For an overview on nanostructures in photovoltaics see [48].
- *Molecular Beam Epitaxy (MBE)* as it enables the growth of some materials in higher quality than MOVPE (e.g. [49, 50]).
- *New materials* are being developed, which offer beneficial bandgaps and lattice constants, e.g. GaInNAsSb [51].
- *Spectrum-splitting* architectures split the solar spectrum and direct the light toward single- or dual-junction solar cells with adequate absorption ranges (e.g. [52-55]). Thereby the challenge of lattice-match is circumvented. Several devices in prototype stage have already been realized.

In the remainder of this paper some investigated concepts, which use and combine elements of this toolbox for III-V multi-junction solar cells will be exemplarily discussed. Note that only an incomplete overview can be given. For more detailed reviews see for example references [7, 19, 56-58].

### *3.1 Upright metamorphic growth on Ge*

The large excess current in the bottom cell of the lattice-matched triple-junction results from the high bandgap 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 in total higher theoretical efficiencies and higher energy yields can be achieved [24, 59]. Such a bandgap combination can be realized by increasing the Indium 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 would cause misfit dislocations and poor material quality. The effect of dislocation can be reduced through the implementation of buffer structures between the Ge and the GaInAs subcell, which increase the lattice constant gradually [24, 60]. Corresponding metamorphic triple-junction solar cells have already been realized with efficiencies above 40% under concentrated sunlight [24, 25]. Theoretical calculations underline that there is still room for significantly higher efficiencies [59].

### *3.2 Inverted metamorphic growth*

In recent years efficiencies above 40% (AM1.5d) have been reached with inverted metamorphic growth (IMM) [2, 23, 28, 30, 31]. 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. Liftoff techniques are used to remove the substrate from the top cell after growth. 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, 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 more flexible as the cell is grown epitaxially and not created in the Ge substrate. Economically a cost benefit in production could arise if the same substrate is used for several epitaxial runs. Yet, this might be counterbalanced by higher production costs and lower yield due to the complexity of cell processing. For space applications the possible lower power to mass ratio and 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. [23, 27-31]). Yet, the approach is not limited to three junctions and IMM cells with four, five and six and five subcells are also investigated (e.g. [20, 23, 32]). A recent combination of upright and inverted growth – called bifacial growth – is also noteworthy. Subcells are grown on both sides of a GaAs wafer with a metamorphic GaInAs bottom cell being grown first on the wafers' backside. After flipping the wafer in the MOVPE reactor a GaAs middle and a GaInP top cell are grown lattice-matched. One technological advantage is that the substrate within the structure protects the upper two cells from dislocations originating from the metamorphic growth on the other side of the wafer. The approach has recently led to an efficiency of 42.3% (AM1.5d, 406 suns) [61].

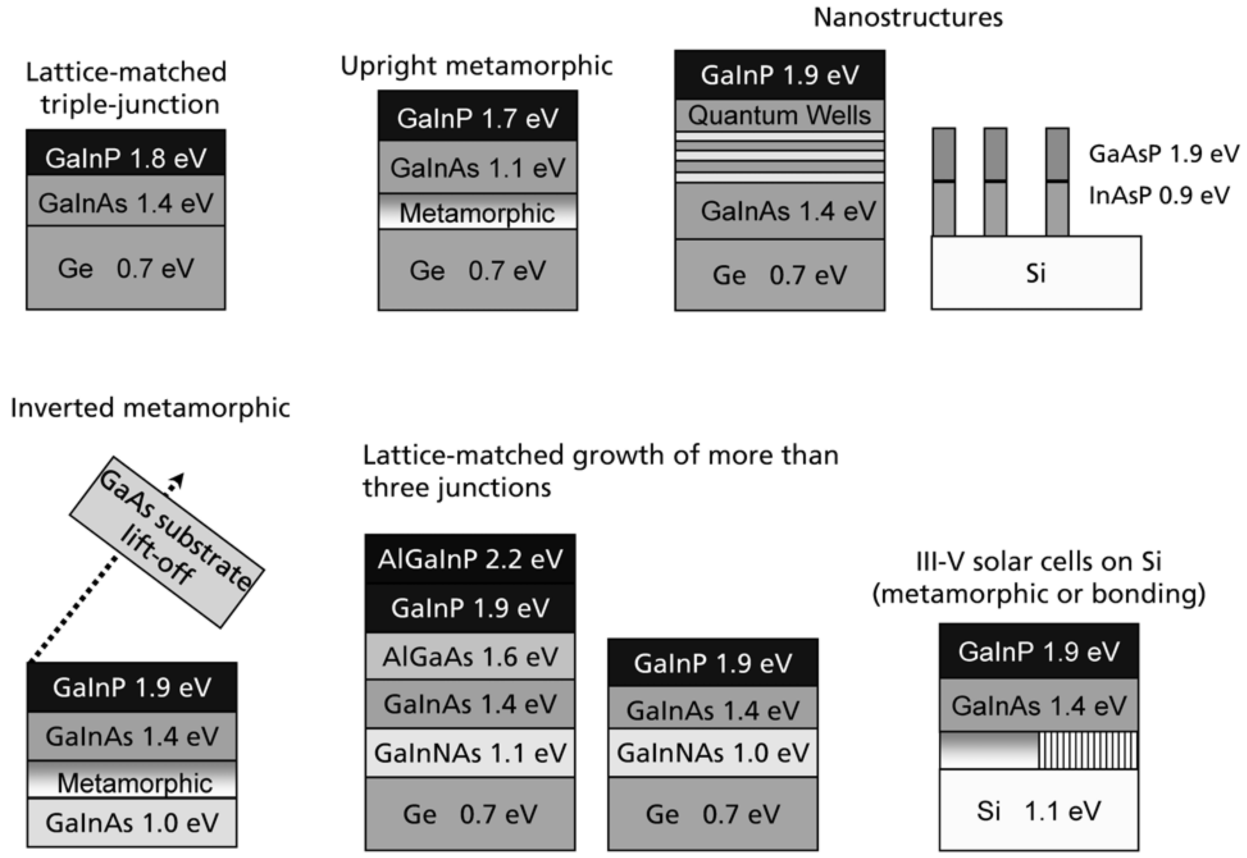

**Figure 3**: Schematic illustration of some currently investigated III-V multi-junction solar cell concepts. Fraunhofer ISE is carrying out research on all of these concepts. Note that several other concepts are also being investigated worldwide and at Fraunhofer ISE. Some concepts have also been realized with different materials and band-gap combinations.

### 3.3 Wafer-Bonding

The technology of wafer-bonding allows combining independently grown (multi-junction) solar cells. Usually one stack is grown inversely. The cells are then in principle just pressed together in a bonding process followed by a liftoff process to remove the substrate. The total process is technologically challenging. Yet, promising results have already been achieved (e.g. [33-37]).

Wafer bonding is for example used to create multi-junction solar cells with more than three junctions. A semiconductor-bonded four-junction solar cell (1.9/1.4/1.0/0.73 eV) recently achieved an efficiency around 31% under AM0 [36]. A five-junction solar cell with 31.7% under AM0 is presented in Ref. [35]. Three upper subcells of AlGaInP (2.0 eV), AlGa(In)As (1.7 eV) and Ga(In)As (1.4 eV) were grown inverted on a GaAs or Ge substrate and then combined via wafer-bonding with subcells of GaInPAs (1.1 eV) and GaIn(P)As (0.8 eV). The latter were grown upright on an InP substrate. All subcells are grown lattice-matched to the GaAs or InP substrate.

Wafer-bonding is also used to realize III-V solar cells on comparably cheap Silicon substrates – as discussed in the following section.

### 3.4 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 between Si and GaAs. Two different approaches are being investigated to overcome this difference: wafer-bonding and direct growth on the Si substrate.

Promising results for wafer-bonding of III-V materials on Silicon substrates have already been achieved (e.g. [33, 34]). Recently a wafer-bonded GaInP/GaAs//Si triple-junction solar cell was realized with an efficiency of 23.3% (AM1.5d, 24 suns) [37]. 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.

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 [62]). One option is the creation of a Ge layer either directly or through the use of SiGe compounds (e.g. [63]). 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. [62, 64]). GaAs or GaInP solar cells on Si substrates have already been realized (e.g. [63, 65]). However, buffers need to be improved in order to achieve efficiencies closer to the theoretical potential of this approach. A strategy for direct growth on Silicon substrates without the necessity for buffer layers is to use dilute nitrides (GaIn)(NAsP), which allows choosing lattice-matched materials to Silicon. However, short diffusion length of minority carriers currently limit this approach (e.g. [66]).

### 3.5 Lattice-Matched growth of more than three junctions

The straightforward approach for III-V multi-junction solar cells with more than three junctions is to grow lattice-matched on Ge substrates. Theoretical calculations show that a 1 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 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. [20, 66, 67]). However, the current world record triple-junction solar cell with an efficiency of 44.0% (AM1.5d, 942 suns) is composed of GaInP/GaAs/GaInNAs [2]. This device was grown by 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.

For MOVPE growth an option to work around the limited GaInNAs subcell is to move to five- or six-junction solar cells, which require lower currents for each subcell. Several such devices have already been realized with promising efficiencies (e.g. [20, 67, 68]).

## 4. CONCLUSION

Various novel designs for III-V multi-junction solar cells are being investigated to reach higher efficiencies than the lattice-matched triple-junction solar cell. Some concepts have already been realized with efficiencies beyond 40% under concentrated sunlight. Many others are still in prototype status, but show great promise concerning efficiency and cost reduction. The heterogeneity of these approaches is based on the wide range of available III-V semiconductors and on the extensive toolbox of technological methods that can be used. These give room for creativity and new ideas. Thus, even more concepts will be developed in the near future. It can be expected that efficiencies towards 50% will be reached within the next decade.

## 5. ACKNOWLEDGMENTS

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