OVERVIEW ABOUT TECHNOLOGY PERSPECTIVES FOR HIGH EFFICIENCY SOLAR CELLS FOR SPACE AND TERRESTRIAL APPLICATIONS

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ABSTRACT: III-V multi-junction solar cells have become standard in space and in terrestrial concentrator systems. 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. 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. This paper gives an overview about the technology perspectives and research trends in III-V multi-junction solar cells. Eventually, a new record efficiency value of 44.7% @ 297xAM1.5d for a 4-junction wafer-bonded solar cell is presented.
Keywords: III-V Semiconductors, Multijunction Solar Cell, Concentrator Cells, Space Cells

1 INTRODUCTION

Increasing the efficiency of a photovoltaic device is the aim of many research projects. A higher efficiency produces more electrical power on a smaller area, i.e. less material is needed. This opens a path for being more cost-effective and allows for business opportunities. III-V based solar cells are a good example. As they are composed of compounds of elements from groups III and V of the periodic table, the bandgap of these semiconductors can be varied by changing their composition. Highest efficiencies can be achieved by adapting the bandgap to the spectrum of the sun. Therefore, there has been an R&D interest in III-V compound solar cells for a long time. However, although the highest efficiency for any single-junction solar cell of 28.8% under the reference spectrum AM1.5g (1000 W/m^2; IEC 60904-3, ed. 2), which is applicable for flat plate terrestrial applications, has been demonstrated for a GaAs solar cell [1, 2], the processing and the material itself is much more expensive compared to other semiconductors (Si, CIGS, CdTe). Due to the comparably high costs per Watt, the only possible entry market for III-V solar cell was space applications. Here another cost measure is of importance: the cost of power per weight. In addition, solar cells in space need to operate under harsh environmental conditions as high-energy protons and electrons harm the semiconductor material leading to a continuous degradation of solar cell efficiency. The speed for the degradation depends on the orbit where the spacecraft flies. Eventually it turned out, that GaAs solar cells are more radiation hard than solar cells made of Si. This opened a market for the III-V based solar cells in space.

The real breakthrough has been achieved when III-V-based multi-junction solar cells were introduced, as they provide higher efficiency than single-junction III-V solar cells without a significant increase of production costs. As a consequence, Si solar cells disappeared from the space market and today nearly all space solar cells are made of III-V multi-junction solar cells. The relatively stable space market led to a continuous improvement of III-V multi-junction solar cells. Today typical industrial efficiencies are in the range of 30%. Note that efficiencies for space solar cells are measured under the extraterrestrial reference spectrum AM0 (1367 W/m^2). Efficiencies under AM0 are typically lower than terrestrial efficiencies under AM1.5g for a specific solar cell.

A cost-effective use of high-efficiency multi-junction solar cells on Earth is enabled in high-concentrating photovoltaic (HCPV) systems. Here, the optical concentration factor is typically higher than 300. 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 – driven by space application - 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 using III-V-based multi-junction solar cells is increasing continuously [3]. For both, the space and the terrestrial market the high efficiency of the multi-junction solar cell is essential. As already mentioned above, space solar cells are rated with the standard spectrum AM0 (1367 W/m^2; ISO 15387, ed. 1), whereas terrestrial concentrator solar cells are rated according to the recently introduced reference spectrum AM1.5d (1000 W/m^2; ASTM G-173-03 direct). Standard testing conditions for all mentioned reference spectra include a temperature of 25°C. For concentrator cells the concentration ratio of the incident light also needs to be considered. It is usually noted in "C suns" meaning an intensity of C-times 1000 W/m^2. As the voltage of a solar cell increases logarithmically with the concentration, efficiencies under concentrated light are always higher than one-sun efficiencies. Figure 1 shows the solar cell efficiency increase over time. Recent laboratory records were set by a triple-junction solar cell with 44.4% under AM1.5d (302 suns) [2, 4] and a five-junction solar cell with 35.1% under AM0 [5]. It is important to note here, that laboratory record solar cells are transferred to an industrial product in a very short time period.

Figure 1 also shows that the increase in efficiency was continuous with roughly $1\%_{abs}$ per year. Indeed the race is still ongoing and new records are published frequently. For terrestrial concentrator solar cells, efficiencies are expected to rise towards 50%, whereas for space solar cells 40% is possible. In order to achieve these goals new cell architectures are necessary. However, to approach the above mentioned efficiency targets, material optimization must be done and new solar cell architectures need to be introduced. In this paper we summarize some technology paths which are currently investigated in the III-V research community and at Fraunhofer ISE. A similar overview has also been presented in Ref. [6]. Most of the paths aim for higher efficiencies, however, there are also interesting approaches to lower the cost by substituting for example the expensive Ge or GaAs substrates by much cheaper Si substrates.

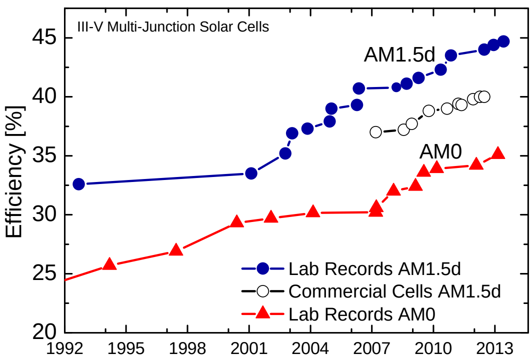

Figure 1: Efficiency records of laboratory III-V multi-junction solar cells under AM1.5d (different concentration ratios) and AM0. Average efficiencies of commercial concentrator solar cells under AM1.5d are also indicated. (AM1.5d lab records according to Green et al. from [7] to [2]; AM0 lab records based on [8, 9] and various individual publications; AM1.5d commercial efficiencies averaged from company product sheets.)

2 CURRENT RESEARCH TRENDS

The state-of-the-art approach for space applications and terrestrial concentrator systems is the use of the lattice-matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction solar cell. Figure 2 shows a typical structure of this device.

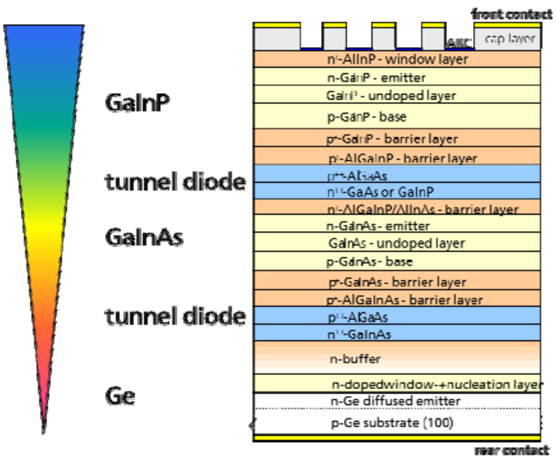

Figure 2: Typical structure of a $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction solar cell, which is the industrial standard for III-V multi-junction solar cells.

The structure is grown with high throughput within commercial metal-organic vapor phase epitaxy (MOVPE) reactors. A p-doped Germanium substrate is used. During growth of the III-V layers an n-doped emitter is obtained by a diffusion process. All III-V-compound semiconductors in this structure have the same lattice constant as the Ge substrate, which facilitates crystal growth with high material quality. 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 determined by the minimum current of the individual subcells. 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 [10] and average production efficiencies are approaching 40% under concentrated light (e.g. [11-13]) and 30% for space solar cells (e.g. [14]). 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 tool box 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.

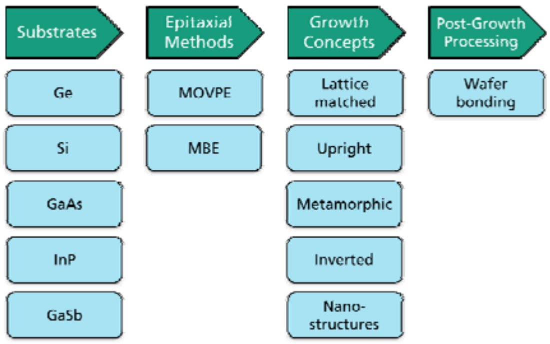

Figure 3: Technological tools and processes which are used to design new high-efficiency III-V multi-junction solar cells.

First, Ge could be replaced by other substrates, e.g. to lower the cost of the device through the use of Si substrates (for example [15-18]) or to realize new architectures (e.g. with InP [19, 20]). Second, for compound materials like GaInNAs, MOVPE growth technology showed deficits. Therefore, molecular beam epitaxy (MBE) is under consideration, e.g. [21-23]. Third, several growth concepts extend the degree of freedom to design multi-junction solar cells:

- *Metamorphic growth* of monolithic materials with different lattice constants. For sufficient material quality buffer structures are usually implemented to gradually transfer the lattice constant (e.g. [24-27]).
- *Inverted growth*: here the top cell is being grown first followed by the other subcells. This allows growing the upper cells lattice-matched to a substrate as buffers are postponed to later growth phases hence ensuring high material quality in metamorphic structures (e.g. [13, 28-33, 34]). Note that these structures have to be flipped, stabilized and the substrate has to be removed during the solar cell fabrication process.

- *Nanostructures* such as multiple quantum wells (e.g. [35-38]) or quantum dots (e.g. [39, 40]) 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 [41, 42]. For an overview on nanostructures in Photovoltaics see [43].

Eventually, after growing the semiconductor material the post growth processing, chemical structuring, metallization and antireflection coating takes place. Recently, the wafer bonding technology has been introduced to stack separately grown (multi-junction) solar cells with different lattice constants (e.g. [17, 44-47]), for example to produce solar cells with more than three junctions

In the remainder of this paper 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 [48-52].

2.1 Novel Lattice-Matched Designs

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 1.0 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. [10, 53, 54]). 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 [55, 56]. 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.

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 [57]. Several such devices have already been realized with promising efficiencies (e.g. [10, 54, 58]).

2.2 Metamorphic Growth

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 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 [24, 59]. 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. [24, 26]. 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 higher efficiencies [59].

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 [60]). One option is the creation of a Ge layer either directly or through the use of SiGe compounds (e.g. [16]). 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. [60, 61]). GaAs, GaInP and AlGaAs solar cells on Si substrates have already been realized (e.g. [15, 16, 62]). Recently, a GaInP/GaAs dual-junction solar cell on Si with an Ga(As)P buffer achieved an efficiency of 16.4% under AM1.5g [18]. 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 [13, 30, 32, 33, 55]. 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, 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 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. A 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. [13, 29-33]). Indeed, record efficiencies for triple-junction solar cells for AM1.5g and 302xAM1.5d of 37.2% and 44.4%, respectively, have been presented by Sharp [4]. Yet, the approach is not limited to three junctions and IMM cells with more subcells are also investigated (e.g. [10, 13, 34]). For example, for space application an inverted metamorphic four-junction solar cell with two buffers has been developed by Emcore and achieved an efficiency of 34.2% (AM0) [34].

A 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) [63].

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 cells. 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. [44-47, 64]).

Results for wafer-bonding of III-V materials on Silicon substrates have been published in (e.g.) [44, 45]. A wafer-bonded GaInP/GaAs//Si triple-junction solar cell was realized with an efficiency of 23.3% (AM1.5d, 24 suns) [17] 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. A semiconductor-bonded four-junction solar cell recently achieved an efficiency of 33.5% under AM0 [47, 65]. A five-junction solar cell with 35.1% under AM0 and 37.8% AM1.5g is presented in Ref. [5]. A triple-junction upper cell of AlGaInP (2.2 eV), AlGa(In)As (1.7 eV) and Ga(In)As (1.4 eV) was grown inverted on a GaAs or Ge substrate and then combined via wafer bonding with a dual-junction lower cell of GaInPAs (1.05 eV) and GaIn(P)As (0.73 eV). The latter was grown upright on an InP substrate. All subcells are grown lattice-matched to the GaAs or InP substrate respectively.

More 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 [66]. The structure consists of a GaInP/GaAs dual-junction wafer bonded to a GaInAsP/GaInAs dual-junction. A new record efficiency of 44.7% (AM1.5d, 297 suns) has been achieved (see Figure 4).

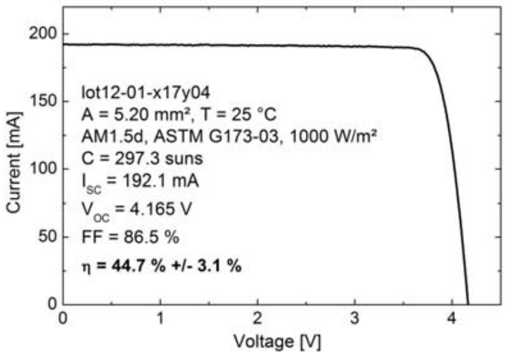

Figure 4: I-V-curve and performance data of the record four-junction concentrator solar cell consisting of GaInP/GaAs//GaInAsP/GaInAs and fabricated using wafer bonding technology. The measurement was conducted at the CalLab of Fraunhofer ISE.

3 CONCLUSION

III-V-based multi-junction solar cells have achieved the highest conversion efficiency of sunlight into electricity and outperform all other materials. In this paper we present a new record value of 44.7% (297xAM1.5d) for a terrestrial concentrator solar cell. For space applications efficiencies as high as 35.1% (AM0) have already been reported. These record efficiencies have been achieved with laboratory cells, however, in the past it was shown that within a very short period of 2-3 years these cells become industrial products. III-V multi-junction solar cells are standard in space applications and in the growing terrestrial market of high concentration PV.

The next goals for space and terrestrial concentrator solar cells are to overcome the 40% and 50% mark, respectively. New tools and processes must be included into the fabrication process to achieve these goals. In this paper we gave an (not complete) overview about newly applied techniques like metamorphic and inverted growth, the efforts to develop new and better materials by using also alternative growth methods and last but not least the wafer bonding process. The combination of these different technologies and processes opens a wide range of possibilities for designing new cell architectures and to approach higher efficiencies. The recent progress in the development of III-V multi-junction solar cells is impressive (see Figure 1) and will continue.

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