III-V Solar Cells

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Abstract— In this review article solar cells based on III-V materials are addressed, starting by a brief description of their operation principle, including key materials’ issues. Subsequently, the different types of III-V solar cells are presented, together with their state-of-the-art performance. Various approaches to reduce their costs are then discussed, and an outlook of the research in this field concludes the paper.

Index Terms—photovoltaics, III-V materials, solar cells.

I. INTRODUCTION

Photovoltaic cells have since 1954, when the first device based on a Si pn junction was presented by Bell Lab researchers [1], been intensely investigated for the conversion of solar irradiation into electric power. Nowadays, many different technologies, meaning type of materials, design of structures, combination of materials and fabrication steps are used to produce a myriad of solar cells. Their performances vary in terms of the numerous figures of merit that can characterize them, amongst which the power conversion efficiency, generated electric power per incident optical power, is the most significant. Since 1976, NREL has been publishing an annual chart with the evolution of the conversion efficiency for most of the existing technologies of solar cells [2]. Today the efficiencies can vary from 13.0% to 47.6% for dye-sensitized cells and multi-junctions with III-V materials, respectively.

One may ask why investing in technologies which provide relatively low efficiencies when there are high efficiency alternatives. The relevance of a certain technology relies on which parameter is the priority for the desired application. If solar cells are required for autonomic toys, low price is priority at the expense of efficiency or lifetime, while for space applications efficiency per unit area or per weight become the most important parameters. Obviously, a long lifetime is also mandatory in the latter case. New applications such as drones or small cube satellites require, as main parameter, light photovoltaic cells. However, price has also become an important issue in these cases, as, for instance, about 25% of the small satellites’ price are the solar cells. It is also important to consider the cost of production of the solar cell when aiming at power plants in order to compete with the present-day ones based on non-renewable energy sources, like fossil fuels. Another notable parameter is flexibility that gives solar cells the capability of adapting to different surfaces, enlarging the range of applications. If solar cells can be incorporated into tissues, it becomes possible to have wearables generating electric power with many civil and military uses. The flexibility can also be very useful for satellites because they can be folded occupying a small area for launching, and be opened when already in orbit. Another advantage of flexibility is the fact that in most cases it implies in lighter weight, which always brings benefits.

Needless to say, the dream goal is to have highest efficiency with lowest cost, longest durability, lightest weight and flexibility. However, today this combination of ideal parameters is not yet possible, but researchers worldwide are working earnestly to achieve this goal or, at least, to get as close as possible to it.

Solar cells fabricated with different materials have specific theoretical conversion efficiency limits, which depend on their absorption strength and wavelength range, charge carrier lifetime and morphological quality. The III-V single crystal material family is the one that can reach the highest efficiencies and, in fact, is the one that holds the experimental record efficiency [2-4]. Despite having also a long term stability in terms of figures of merit, they are very expensive, hard and heavy. The efficiencies achieved so far for single junction devices are very close to the theoretical limit, so there is not much more that can be improved. On the other hand, there is still a lot of room for progress in lowering the fabrication costs and using light flexible substrates, therefore, recently much emphasis is being given to these research topics. Although costs cannot be reduced to the level of amorphous or organic solar cells, for example, a significant reduction would immensely broaden the range of applications.

In this review article the principle of operation of III-V single crystal solar cells including materials’ issues will be described in session II. Session III will present different architectures and concepts for III-V photovoltaics, including single junction, multi-junctions and quantum-based solar cells, using quantum wells, wires and dots. The investigated approaches to reduce costs and use alternative cheap and/or flexible substrates will be addressed in session IV. Concluding remarks and an outlook to the future will comprise session V.
II. FUNDAMENTALS OF III-V SOLAR CELLS

Inorganic solar cells in general work based on an illuminated pn-junction, which incident photons with energy $h\nu > E_g$, the material bandgap, promote electrons from the valence band to the conduction band, leaving a hole behind. The created electron-hole pairs are separated by the junction intrinsic electric field, which points from the $n$-type material to the $p$-type. In the open circuit condition, the electrons accumulate in the $n$-type side and the holes in the $p$-type side, reducing the intrinsic electric field and, therefore, generating a potential difference across the junction in the direction opposite to the intrinsic electric field, named open circuit voltage, $V_{oc}$. The appearance of this voltage is called the photovoltaic effect. On the other hand, under short-circuit condition, the separated electrons and holes move in opposite directions towards their respective contact layers, generating a current, called short-circuit current, $I_{sc}$. Since the current flows from the low to the high voltage terminal, power can be delivered to an external circuit, whenever the device is neither in the open nor in the short circuit condition. A detailed description of the physics of solar cells is beyond the scope of this feature article. Excellent review articles and books are available to the interested reader [5-8]. As mentioned before, the first physical mechanism for the solar cell operation is the absorption of photons from the solar spectrum. Thus, the materials forming the pn-junction should have a bandgap energy compatible with the solar spectrum. The well-known Shockley and Queisser efficiency limit (S-Q) [9] for a single junction solar cell as a function of material bandgap is shown in Fig. 1 for unconcentrated and concentrated 6000 K black body radiation and for unconcentrated AM1.5d and AM1.5g [10]. According to the presented data, for all the different spectra, the material bandgap range between 1.0 and 1.5 eV maximizes the efficiency. The two most important III-V materials, namely GaAs and InP, happen to have a bandgap within this range, as other different III-V alloys also do, as depicted in Fig. 2, hence the great interest in using III-V semiconductors for fabricating solar cells. Moreover, excellent quality materials can be routinely produced by the standard techniques such as metalorganic vapor phase epitaxy (MOVPE) or molecular beam epitaxy (MBE), MOVPE being preferred by the industry.

In the case of single junction solar cells, ideally a GaAs homojunction is used. The material is grown on top quality substrates available in the market. However, when heterojunctions or multi-junctions are needed for advantageous coverage of the solar spectrum, III-V materials with a different bandgap are required. For good quality material, the lattice parameter of the different deposited layers should be the same as that of the substrate [11]. Materials with a defect density higher than $1 \times 10^6 \text{cm}^{-2}$ will most certainly give rise to solar cells with low short circuit current due to charge carrier trapping and low shunt resistance, leading to significant current losses [12]. As can be seen in Fig. 2, Al,Ga$_{1-x}$As, Al$_{0.5}$In$_{0.5}$P or In$_{0.5}$Ga$_{0.5}$P, for instance, can be used for the window or back surface field layers (the role of these layers will be addressed in the next session) in a GaAs device, since they have a larger bandgap and essentially the same lattice parameter. However, in some cases there is not a III-V material which can meet the bandgap and lattice parameter requirement simultaneously. The multi-junction solar cell (MJSC) concept is one example which faces this difficulty. The idea behind MJSCs is to stack two or more solar cells with appropriate bandgaps so that each one absorbs a certain portion of the solar spectrum. By doing so, the power conversion efficiency can be maximized by reducing the transmission or thermalization losses. In order to optimize the efficiency, the bandgaps of the different materials should be chosen so that the absorption is balanced between the different junctions. For the two-terminal geometry, the stacked junctions are connected in series, therefore, the total current is limited by the lowest one. Thus, to avoid waste of electron-hole pairs, the generated current should be the same in each junction reaching the current-matching condition, meaning the material bandgaps and thicknesses combination should be chosen accordingly.

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Image 306x234 to 531x396

Fig. 1 Shockley-Queisser efficiency limit for an ideal solar cell versus bandgap energy under ground sun spectrum: a) unconcentrated 6000 K black boy radiation (1595.9 W/m$^2$), b) full concentrated 6000 K black body radiation (7349.0 x $10^6$ W/m$^2$), c) unconcentrated AM1.5-Direct (767.2 W/m$^2$) and d) AM 1.5-Global (962.5 W/m$^2$) [10].

Image 322x410

Fig. 2 Bandgap energy versus lattice parameter for different semiconductor materials.

Image 363x444

Fig. 3 shows the conversion efficiency for MJSCs as a function of the number of junctions for three different solar spectra, namely concentrated AM1.5d, unconcentrated AM1.5g and AM0. The numbers inserted in the colored rectangles are the ideal bandgaps of the different junction materials calculated using the detailed balance theory [13]. Analyzing these numbers taking note of Fig. 2, it is clear that III-V materials are the most suitable for high efficiency solar cells, although it is evident that it is not always possible to have them with the appropriate bandgap and the same lattice parameter of...
III. TYPES OF SOLAR CELLS BASED ON III-V MATERIALS

In this session the state-of-the-art of different types of solar cells based on III-V materials will be discussed. First single and multi-junction solar cells will be presented. Then the present status and the challenges to reach the theoretically predicted improvement of solar cells’ performance by using low dimensional structures as quantum wells, wires and dots will be described.

GaAs is the III-V material that has been a long time the one used in the solar cells with the single junction record efficiency [2]. As mentioned in the previous session, its bandgap of 1.42 eV is ideal to maximize the power conversion (see Fig. 1). The basic structure of a GaAs single junction solar cell (here we use an \textit{n-on-p} structure as illustration) comprises an \textit{n++} doped contact layer (patterned in a comb structure), a thin \textit{n+} doped window layer, which serves both to repel minority carriers (holes) and to passivate the front surface, an \textit{n} doped emitter, a \textit{p} doped base, a \textit{p+} doped back surface field (BSF) layer, with a similar role of the window (in this case electrons are repelled) and a \textit{p++} doped contact layer. A simple scheme is shown in Fig. 4, with the addition of the anti-reflective coating (ARC) in green, which is deposited in the complementary area of the front side comb contact, and the metals (in orange). As a window layer, a transparent material, or one with a relatively large bandgap, is used so that the photons can travel through it and be absorbed mostly at the emitter or base layers, preventing charge carriers from being trapped by surface states. In the case of GaAs, several lattice matched alloys, AlGaAs, InGaP, among others, are available to form the window layer, as can be seen in Fig. 2. The emitter and base layers that form the active region of the device are both of GaAs, and the BSF layer, which is often also of GaAs, can alternatively be of a material with a slightly larger bandgap to form a barrier to reflect the minority charge carriers more efficiently. The record efficiency for the GaAs single crystal single junction solar cell of 27.8% under AM1.5d radiation has been reached in 2017 by the LG group [17]. On the other hand, NREL has recently (2021) presented a device with the record efficiency of 30.8% under concentration [18]. It is interesting to note that already in 1977, GaAs single crystal single junction solar cells had an efficiency of about 22 % under AM1.5d, meaning that in about 40 years there has been an improvement of around 6%. This improvement is mostly related to the material quality. The progress in these years in both the growth techniques themselves and the purity of the source elements used in the deposition are the main responsible for the observed increase in efficiency.

Advanced light trapping mechanisms, using flat mirrors on the back side or patterned reflectors, that help confining both the sunlight and the luminescence inside the structure, have been investigated in order to further increase the device’s efficiency [19-22]. Using such technologies, absorption can be enhanced, generating a higher density of electron-hole pairs, and consequently, a larger short circuit current. The open circuit voltage can also be raised due to a reduction in radiative recombination, as a consequence of both reabsorption and luminescence confinement. Moreover, the absorbing layers can be thinned down saving the costly III-V materials. Ramboud University was the first to use such optical strategies [22], while Alta Devices refined the technology to produce,
a decade later, a device with 29.1% efficiency [2]. Concluding, the efficiency of the GaAs single junction solar cells is very close to the 33 % S-Q theoretical limit, indicating that there is not much room for further efficiency improvements with this technology.

It has been pointed out that InP is much more resistant to radiation damage than GaAs and it has also an interesting bandgap of 1.36 eV for high power conversion efficiency. Therefore, it has been presented as the best candidate for spatial applications. However, the efficiencies achieved using this material have for a long time been short from the expected values, remaining around 22 %, leading the market to choose the already established GaAs solar cells. The difficulty with InP solar cells is the lack of a lattice-matched window material (see Fig. 2). Wanlass has used a doping scheme with layers with two different doping levels to minimize surface recombination and improve the performance of the device, obtaining in 2017 efficiencies above 24 % [23].

The MJSC concept has proven to be the best path for going beyond these efficiencies or the S-Q limit [9]. In order to fully understand the motivation for using multi-junctions, it is helpful to go back to the single junction solar cell, in which the incident photons with energy above the bandgap will promote the electron from the top of the valence band to an energy $h\nu - E_g$ above the bottom of the conduction band. The electron will then in a ps time scale lose this excess energy $h\nu - E_g$ in the form of heat. Hence, the smaller the bandgap, the higher these thermalization losses and, additionally, the smaller the open circuit voltage is, as it is limited by the bandgap to $E_f/E$. On the other hand, larger bandgaps limit the portion of the solar spectrum which can be absorbed, increasing transmission losses and, consequently, reducing the short circuit current. The idea of a MJSC is to reduce transmission and thermalization losses by stacking more than one $pn$ junction, each of materials with different bandgaps. The $pn$ junctions are connected in series so that the effective open circuit voltage is the sum of the individual ones, thus limited by the sum of the bandgaps, and the short circuit current is limited by the lowest one. A scheme with three junctions is shown in Fig. 5. The sub-cells are connected by tunnel diodes which are transparent and reversibly polarized, essentially acting as a short circuit to allow current flow.

Initially, double junction solar cells consisting of GaAs (1.42 eV) and InGaP ($\approx 1.90$ eV) $pn$ junctions, monolithically grown lattice-matched to GaAs substrates, reached about 30 % in efficiency under one sun, a value above that obtained for single junctions, but short from the expected values, according to Fig. 3. The main reason being that the materials’ bandgap energy was too high. In trying to use materials with the bandgap closer to the ideal, double junctions of Si and GaInP, have been obtained both monolithically, requiring metamorphic growth, and mechanically stacked with 4 terminals. These structures have achieved a record efficiency of 23.4% [24] and 32.8% [25], respectively. The combination of Si with III–V materials will be discussed in more detail in the next section. Another interesting approach, which has in 2021 reached the global record efficiency of 32.9 % for double junction solar cells, is the use of strain balanced InGaAs/InGaP multiple quantum wells [26].

The advantages of using nanostructures for solar cells will be further discussed later in this session.

The triple-junction solar cell is the MJSC generally used in the satellites’ market and a few power plants. The most common structure, which has been available from many manufacturers for many years and is the industrial state-of-the-art, is composed of Ge, In$_{0.01}$Ga$_{0.99}$As and In$_{0.5}$Ga$_{0.5}$P $pn$ junctions, grown lattice-matched to the Ge substrate. Although these materials do not have the ideal bandgaps, efficiencies around 41.6 % have already been achieved under AM1.5d and 364 suns concentration [27].

![Fig. 5 Scheme of a triple junction solar cell](image)

In order to further improve the efficiency, several approaches have been followed to increase the solar spectrum coverage with MJSC. Three of them will be described next. The first one is the introduction of a fourth junction of about 1.0 eV bandgap between the Ge and the GaAs cells. In this case, bandgaps of 0.68 eV, 1.01 eV, 1.42 eV and 2.01 eV should be used, according to Fig. 3. Ge is then used for the bottom cell, GaAs for the third and InGaP for the fourth. The second sub-cell could be obtained by introducing N in the InGaAs alloy. However, the charge carriers’ low diffusion length known for the nitride material is the main drawback [28].

In general, the problem with the three or four junctions’ solar cells is not the top or bottom cells. The difficulty is that the ideal materials for the intermediate sub-cells do not have the same lattice parameter as the substrate. A second approach to face this problem is to use the inverted architecture [29]. As an example, the AM1.5d 1000 suns spectrum can be ideally split in a three-junction solar cell if materials with 0.77 eV, 1.21 eV and 1.84 eV are used (see Fig. 3). For the top cell InGaP can be grown lattice-matched to GaAs, followed by an appropriate tunnel diode and then a metamorphic InGaAs (1.21 eV) is deposited. The misfit dislocations of the InGaAs do not interfere in the already grown InGaP cell. Before growing the InGaP layers, a sacrificial buffer AlAs layer, for instance, is deposited. In parallel a Ge solar cell is fabricated. The III–V structure deposited on GaAs is removed by lift-off from the original substrate with the aid of the sacrificial layer and transferred, in the inverted order, to the Ge solar cell. By using this method, Sharp has produced a record efficiency of 44.4 % under AM1.5d 302 sun [30]. Costs can be reduced if the GaAs substrates are reused. The inverted architecture concept was used by the NREL group in the development of the ingenious six junction structure which provides an efficiency of 47.1 % under AM1.5d 143 suns concentration (39.2% under AM1.5g). On a GaAs substrate a series of three lattice matched junctions is grown: first a 2.1 eV AlGaInP, followed by a 1.7 eV AlGaAs and
then a 1.4 eV GaAs. They are separated by an Al$_{0.4}$Ga$_{0.6}$As tunnel diode and a third one is deposited on top of the GaAs junction. Before depositing each of the following three InGaAs lattice mismatched junctions, a compositionally graded buffer layer is grown to minimize the misfit dislocation density. The mismatched junctions have following bandgaps: 1.2 eV, 0.95 eV and 0.69 eV. Between the three InGaAs junctions, a GaAsb/GaInAs tunnel diode is deposited. The inverted structure is flipped and bonded to a Si substrate so as to have the larger bandgap on top, and the original GaAs substrate is etched away before the device is processed [3]. The global record efficiency of 47.6% at 665 suns has been reached this year by the German Fraunhofer ISE, together with the French Soitec, with a four junction structure InGaP/AlGaAs/InGaAsP/InGaAs with bandgap energies of 1.89 eV, 1.47 eV, 1.06 eV and 0.73 eV, respectively. The inverted architecture concept is used to grow the two higher bandgap sub-cells lattice-matched to a GaAs substrate, while the two lower bandgap junctions are grown lattice-matched on an InP substrate. In a second step, the inverted structure is removed from its original GaAs substrate, flipped and bonded on top of the other two sub-cells’ structure. Although the solar cell structure dates back to 2016, a specially designed four-layers antireflection coating has raised the device efficiency by 1.5% [4]. A third approach to obtain junctions with III-V materials having the proper bandgaps, but that unfortunately are not available with the desired lattice parameter, is to use multiple quantum wells (MQWs) [15, 31]. In a quantum well, the fundamental optical transition energy is determined by the bulk material bandgap plus the confinement energy in the conductor and valence bands, which inversely depends on the square of the quantum well thickness. Therefore, the absorption energy can be tuned by the thickness of the quantum well and to a lesser extent by the barrier material composition or the band offsets between well and barrier materials. In the case of using lattice mismatched materials, to avoid the formation of misfit dislocations, responsible for charge trapping, the strain of the full structure should be zero. If tensile strain is compensated by compressive strain in alternating layers, they cancel out producing proper quality material. The thickness and composition of these alloys should both be properly chosen so as to fully cancel the strain. Inspecting Fig. 2, taking GaAs as the substrate, it is clear that one can use a material with a lattice parameter larger than that of GaAs as a QW and a material with a smaller lattice parameter as the barrier. This method is called strain-compensation and in the beginning of the 2000s has been first explored in the InGaAs/InGaP system for improving solar cell power conversion efficiencies [32]. The average strain which should be zero is given by:

\[ \varepsilon = \frac{a - a_s}{a_s} = \frac{\left( A_{QW} L_{QW} a_{QW}^2 + A_B L_B a_B^2 \right) - a_s}{A_{QW} L_{QW} a_{QW}^2 + A_B L_B a_B^2} \]

where \( a \) is the effective lattice parameter of the MQW, \( a_s \) is the substrate well and barrier parameters, respectively, \( A_{QW} \) and \( A_B \) being the elastic stiffness coefficients, \( a_{QW} \) and \( a_B \) the lattice parameters and \( L_{QW} \) and \( L_B \) the layer thicknesses. In determining the appropriate thicknesses, one should note that they cannot exceed the critical value determined by Mathews and Blakeslee [33]. The procedure consists in first choosing an In$_x$Ga$_{1-x}$As composition and thickness for the QW that suits the desired effective bandgap, then determining its lattice parameter. Using equation (1), one can calculate the pairs \( a_B \) and \( L_B \) which will lead to a cancellation of the strain. In the 2010s many researchers have successfully explored this strain balance technique [34, 35], including the introduction of an interlayer to further reduce the strain [36], with significant improvement in the solar cell figures of merit. Winter et al. have theoretically shown that the bandgap of an In$_x$Ga$_{1-x}$As/In$_x$Ga$_{1-x}$P QW can be tuned between 0.7 and 1.3 eV by varying \( x \), \( L_{QW} \) and \( L_B \) and, therefore be useful as one of the junctions in many different MJSC scenarios (see Fig. 1) [15, 37]. For a more thorough review of this topic refer to [16]. This year France et al. have reached the world record efficiency for triple junction solar cells under AM1.5g (39.5%) and AM0 (34.2 %), in which the intermediate sub-cell is a strain compensated InGaAs/InGaP MQW structure [38]. Another type of nanostructure that can be used to improve the performance of solar cells is the nanowire. Nanowires are nanostructures with two dimensions in the nanometer scale and one in the micrometer scale. In general, they are micron long cylinders with a diameter of tens of nanometers. They have three important advantages for photovoltaics, if compared to bulk material or quantum wells. They have a larger surface area to absorb light, they can trap the light if displaced in an array, further enhancing the absorption and, in the case of heterostructures, they can be grown with lattice-mismatched materials, because, given their small lateral dimensions, the strain is released through the lateral surface [39], avoiding the formation of misfit dislocations. The lack of restriction in the lattice parameter gives much flexibility in the choice of materials. Despite these advantages, the growth of nanowires can be challenging. The nanowires can be obtained by top-down techniques, where the bulk material or QWs are deposited by MOVPE or MBE and later, the nanowires are obtained by lithographically etching the structure. However, in this case the advantage of not worrying about the materials’ lattice parameter is lost. Therefore, bottom-up methods such as selective area epitaxy [40] or vapor-liquid-solid [41] should be used. For application in solar cells an array of nanowires should be grown, as shown in Fig. 6, and the processing of these structures to collect the current and passivate the total surface is even more challenging. Theoretically it has been shown in 2016 that an InP based nanowire single junction solar cell could reach 32.5% under AM1.5g, which is about half of a percent better than the same cell made with the same bulk material [42]. Experimentally, in the same year Hultin et al. [43] have presented an InP based nanowire solar cell with a short circuit current 14% lower than that of the best in the market [23], but using only 6% of the volume material. Solar cells based on arrays of tapered InP nanocones having a special nanolens on top have reached 17.8% efficiency under AM1.5g [44].
GaAs nanowires’ arrays have also produced record efficiencies of 15.3% under the same solar spectrum [45]. The state-of-the-art up to now in the field of nanowire solar cells is only in the laboratory level, but these results indicate a potential for them in the future. The question which is often raised, for which there is yet no answer, is if the complexity and consequent high costs for fabricating such cells will be compensated by the gain in efficiency and low volume material used.

Quantum dots, nanostructures which confine the charge carriers in all three dimensions, have also been used for solar cells. In the same way as the quantum wells have been tailored to reach the ideal bandgap, quantum dots buried in a material of larger bandgap have been explored with the same purpose. However, in this case the volume of absorbing material is reduced and the growth of these structures does not have the desired reproducibility. On the other hand, quantum dots can be extremely useful when used in intermediate band solar cells, which can, in principle, overcome the S-Q efficiency limit [46]. This concept relies on the introduction of an electronic energy level within the band gap of a barrier material, allowing for sub-bandgap absorption, increasing the short circuit current, while ideally maintaining the original open circuit voltage. For maximum efficiency, the barrier (matrix) material should, at room temperature, have a bandgap of 1.95 eV and the fundamental electronic energy level of the quantum dot should be 1.24 eV above the matrix valence band and 0.71 eV below its conduction band. A scheme of such electronic structure is depicted in Fig. 7. Given its more established deposition knowledge, InAs/GaAs has been by far the most investigated system, although it does not meet the ideal energy requirements. In 2012 Bailey et al have demonstrated an improvement in efficiency of an InAs/GaAs intermediate band solar cell (14.3%) with respect to a single junction GaAs device (13.8%) [47], as a sort of proof of concept. The achieved efficiencies are still quite short from the theoretically predicted values, mainly due to morphological [48] and electronic [49] defects introduced during the deposition of quantum dots. Methods to reduce the defect density by properly capping the QDs [50, 51] or by using strain compensation [52] have been pursued, resulting in promising achievements, but have not yet led to the desired power conversion efficiencies. In order to approach the ideal matrix material bandgap of 1.95 eV, larger bandgap materials have more recently been both experimentally and theoretically investigated, but with limited success. Some examples with encouraging results are InP/InGaP [53-55], InAs/InGaP [56, 57], InAs/AlGaAs [58] and In(As)P/InGaP [59]. A more detailed discussion of the progress reached with such 0D structures can be found in the review chapter [16], cited earlier.

![Fig. 6 A scanning electron microscopy image of an array of quantum wires of III-V material.](image)

III. APPROACHES TO REDUCE COSTS

In this session, the main hindrance regarding solar cells based on III-V materials will be addressed. Among the aforementioned dream list of high efficiency, low cost, durability, lightness and flexibility, while high efficiency and durability are the strengths of III-V solar cells, their high cost is the main challenge to overcome. Weight and flexibility might also pose technological challenges due to the monocrystalline nature of III-V materials.

Closely analyzing the main requirements for the fabrication of a III-V solar cell such as substrate, III-V material deposition and solar cell structure processing, the bulkiest portion of the total cost is the substrate. For a GaAs single junction solar cell, the substrate may represent more than 80% of the cost of the device, while the III-V deposition by MOVPE and the device processing represent roughly 10% each [60].

Starting by the two less critical issues, even though the III-V deposition and device processing represent a smaller portion of the total cost, comparatively with other solar cell technologies (e.g. Si, organic), they still represent a high value, which must be reduced. Regarding the cost reduction for the device processing, there are studies reported in the literature to optimize the metallic contacts deposition using cheaper materials and with a higher throughput method such as printing [61]. In the case of structures for which wafer bonding and/or substrate recycling are needed, these steps will also require optimization to lower their cost. These cases will be discussed further in this session. Concerning the cost reduction for the III-V deposition, the main approaches consist in either increasing the throughput and reducing the material consumption of the MOVPE system or changing the deposition technique altogether. A higher throughput of the MOVPE system can be achieved by means of developing methods to raise the III-V growth rate or lower the temperature ramps’ time [62]. As for substituting the deposition technique, there have been studies to use Hydride Vapor Phase Epitaxy that can deliver high growth rates, but is still in its early stages of development, when compared with the technologically mature MOVPE technique [63]. Nevertheless, to drastically lower the III-V solar cell cost, one cannot evade tackling the usage of the III-V substrate. The most straightforward option is to avoid the III-V substrate entirely by accomplishing growth of high quality III-V material on top of alternative substrates. A middle ground option is to transfer the III-V thin film grown on a III-V substrate to an alternative substrate, while recycling the III-V substrate for subsequent growths.

![Fig. 7 Electronic scheme of an ideal intermediate band solar cell.](image)
Historically, epitaxy of III-V material on top of alternative substrates has always been of interest. Notably, the integration of III-V and Si, not only for solar cells but for optoelectronic devices in general, has fueled research in direct epitaxy of III-V on top of Si. However, even with all the enormous efforts put into this goal, the challenge to grow high quality III-V material is yet to be reached. There are many obstacles for direct epitaxy of III-V on Si such as the difference in lattice parameter (e.g., from GaAs to Si), polarity (III-V polar, Si non-polar) and thermal expansion coefficient \([64]\). All these differences contribute to the generation of defects within the III-V structure, which results in impaired performance of the devices. There are some reported strategies to handle these defects, involving the growth of a metamorphic buffer layer (either a III-V layer like GaP or a SiGe layer) or a diluted nitride layer lattice matched to Si \([65, 66]\). A promising target that has gathered interest in past years is to build tandem solar cells using the Si not only as a substrate, but also as one of the junctions (see Fig. 8a). The III-V on Si tandem solar cell is an auspicious candidate to reach efficiencies higher than those of Si solar cells while keeping a low cost, since the expensive III-V substrate is out of the equation. Unfortunately, its efficiency today offers no improvement, when compared to the record value for Si single solar cells. In 2021, the record efficiency of 25.9% was set for the III-V on Si tandem solar cell under AM1.5g with a triple junction InGaP/GaAs/Si using a novel AlGaAsP metamorphic buffer layer \([67]\). One promising alternative to integrate III-V on Si and avoid the influence of lattice mismatch are the nanowires. But, as mentioned before, it is yet to be determined if the negative effect on cost, due to the increase in complexity of their growth, can be overcome. Although direct epitaxy of III-V on Si has not yet delivered the promised high efficiency of solar cells, transferring the III-V thin film to an alternative substrate has led to better results. As of today, there are two methods that have given the best results. They are: mechanically stacking the III-V thin film on top of the Si solar cell (see Fig. 8b) or bonding the III-V thin film to the Si solar cell (see Fig. 8b). The mechanical stack method consists in adhering the III-V and the Si with a transparent dielectric material. In this case the III-V and the Si solar cells are electrically insulated from each other. They can be optimized independently, but, on the other hand, they have four terminals, instead of two. The record efficiency achieved with this method is 32.8% for a dual junction and 35.9% under AM1.5g for a triple junction InGaP/InGaAsP/Si solar cell \([68]\). In order, for any of these transfer methods, to reduce costs of the final device, the III-V substrate that was used to grow the III-V film needs to be recycled, i.e., reused in multiple growths. For substrate recycle, the process epitaxial lift-off (ELO) is a key procedure to separate the III-V thin film from the substrate, keeping the latter still mostly intact. In this case, a sacrificial layer is grown between the substrate and the device structure and is later wet-etched by specific chemicals, which should not damage the substrate or the thin film. In addition, after substrate removal, a polishing process, Chemical Mechanical Polishing (CMP), needs to be performed to restore the substrate for epitaxy. Both the ELO and CMP processes are yet to be optimized and could result in higher costs to the solar cell fabrication \([69-70]\). Until today the substrate of the III-V on Si tandem solar cells with record efficiencies, mentioned earlier, has been entirely etched away, given the complexity of the ELO process. According to Essig \textit{et al.} \([25]\), for a viable low cost III-V on Si solar cell using transfer method, the III-V substrate should be recycled at least 50 to 100 times. III-V thin film solar cells can also be transferred to flexible substrates. As in the case of rigid substrates, the transfer does not affect the device performance, maintaining their original efficiency \([71, 72]\). Namely, GaAs single solar cell on a flexible substrate (see Fig. 8d) has provided a record efficiency of 25%, while a triple junction solar cell, also on a flexible substrate, has reached 43% efficiency \([21]\). Even though these novel approaches to reduce the costs of the high efficiency III-V solar cells need to advance further, their present performance and the promised lower costs have led many research groups in the field to foresee a bright future for them in photovoltaics. Si solar cells have been stagnant in terms of power conversion efficiency in the past decades with a value of around 27% \([2]\). Tandem solar cells with Si are investigated using a wide range of low-cost materials’ combinations (organic, perovskite) with the aim of increasing the efficiency. However, most of the attempts still fall short in performance, even when compared with single Si
solar cells. Only recently a perovskite/Si tandem solar cell reached an efficiency higher than that of a single Si solar cell in laboratory conditions [2]. Furthermore, these non-crystalline materials have additional problems with short lifetime and instability. III-V on Si on the other hand has been predicted to dominate the photovoltaic market in 2050, if all the goals for lowering costs are met, going from a basically zero market share today to a 70% in 2050 [73], or to 30% in a more conservative scenario of a continuous development.

IV. CONCLUSION AND OUTLOOK

The III-V solar cells, since their infancy, have presented the highest power conversion efficiency compared to all other technologies [2]. Surprisingly, there is still room for improvement with this technology, if we compare the theoretical limits to the record efficiencies already achieved. Material quality and design, anti-reflection coating layout, light confinement strategies are some of the approaches that have greatly contribute to the improvement in performance of these devices in the last 40 years, and which can still be further optimized. Even though the different investigation approaches can lead to an increment in efficiency, the cost of these devices is the crucial parameter that will determine their place in the market. Therefore, reducing the costs by using alternative substrates, optimizing the different processing steps, increasing the throughput of the material deposition or decreasing the amount of high price material used in the epitaxy are topics on which most of the action in the field should be focused, if they are to play a leading role in photovoltaics.

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