The Role of III-V Semiconductor Materials and Compounds in Thin film Solar Cell Technology from 2018 to 2023: A Review

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ABSTRACT

In the realm of solar power generation, III-V semiconductor-based solar cells are garnering global attention and are very essential to a country's scientific and economic development. Because of their direct band gap, high optical absorption coefficient, greater power conversion efficiency, and chemical stability, these materials and their compounds are mostly employed in solar cell technology. Here, a brief review of the development and application of III-V semiconductor thin film technology has been covered. On the other hand, the significant inventions and thin film solar cell designs from 2018 to 2023 have been reviewed. There is also discussion of many processes, tools, and preparation methods that were employed during this time to enhance the solar cells' efficiency and photoelectrical properties. We discussed the new issues related to flexible solar cells, Al-free solar cells, Ni and Bi-used solar cells, and hole selection solar cells. The photovoltaic parameters such as V_{OC}, J_{SC}, FF, and power conversion efficiency have been changed for prepared solar cells under various circumstances, highlighted.

Keywords: Thin film, Solar Cell, III-V thin film, GaAs.

I. INTRODUCTION

Thin film Solar cells are made of photovoltaic materials and are the devices that convert the light energy (especially from sunlight) to electrical energy. Photovoltaic materials deposited on the substrate, such as glass, quartz, semiconductors, plastic, ceramics, mica, polymers, metal alloys, insulators, and organic materials, which are used on solar cells, absorb the photon from the light and transfer the energy in the form of electricity. The thickness of the thin film solar cell is varying from a few nanometers to a few micrometers, which depends on the solar cell application. The work on the thin film solar cells was originally begun by the researchers from the Institute of Energy Conservation at the University of Delaware, United States of America, in the 1970s, but there was not significant output until the 1980s. Atfer two-decade progress, in 2000, the Nobel Prize in physics was given to Zhores Alferov and his Loffe Institute team for their work creating the first gallium arsenide (GaAs) heterostructure solar cell, whose efficiency over then 26% in a laboratory environment provided more opportunity for robotic work [1]. The photovoltaic solar cell technologies, earlier used, were based on single-junction silicon, but currently use mulit-junction thin layers of materials such as binary materials (GaAs, CdTeb), ternary materials (InGaAs, CIGS (copper indium gallium selenide)), and quaternary materials (AlInGaP, InAsSbP), whose higher ionicity increases the band gap than lesser ionic compounds [2]. The light conversion efficiency of a single-junction thin-film GaAs solar cell reaches more than 29% [3]. In the future, innovative and more efficient thin films such as dye-sensitized, perovskite, CZTS, organic, and quantum dots, which lead to fewer environmental impacts, human toxicity, and heavy-metal emissions, will be used in solar cells and space technology [4].

Compared to other group materials and their compounds, Group III-V semiconductor materials and their compounds offer better qualities for high energy conversion efficiency, making them far more useful for contemporary microelectronics. Furthermore, compared to other modules, group III-V thin film solar cells have three orders of magnitude less area needed and are more radiation hardy, which creates a new avenue for high-energy solar cells and makes them more affordable [5]. This article summarizes the developments and ongoing research being done on III-V semiconductor thin-film materials and compounds related to solar cells and renewable energy sources. In the first section of our evaluation of the literature, we have outlined the milestone's progressive research works on important III-V semiconductor thin film compounds up to 2023. In the second section, we have discussed the research works done from 2018 to 2023 on the III-V semiconductor thin film materials and compounds. Finally, we will conclude and give future research scope on it.

II. LITERATURE REVIEW

Utilizing silicon-based solar cells, including c-Si, α-Si, and others, has significant drawbacks due to their high cost. Therefore, research into substitute materials that are more affordable and have higher power conversion efficiency than silicon-based solar cells is necessary. In comparison to silicon materials, III-V semiconductor materials are less expensive and offer better photoelectric characteristics. Here is a summary of some significant advancement in III-V semiconductor thin-film compounds that have been made up to 2023.

In the early decade 1901 to 2000, the milestone works can be pointed out as follows: (1) In 1950, the first solar cell was produced by Bell Labs for space activities. (2) In 1970, the first highly effective GaAs heterostructure thin film solar cell was introduced by some researchers of the Institute of Energy Conservation in the United States [6]. (3) In 1972, there was established the world's first laboratory for photovoltaic research and the first time development of a thin-film photovoltaic solar cell. (4) In 1974, the Florida Solar Energy Center was started by the Florida Energy Committee and the Florida State Legislature [7]. (5) In 1981, the first time demonstrated more than 9% efficient thin film solar cells using copper indium sulfide ($CuInS_2$) and Cadmium Sulfide (CdS) materials. (6) In 1986, the world's first commercial thin film power module, 'G-4000' was made by ARCO Solar. (7) In 1994, the GaInP/GaAs was the two-terminal concentrator solar cell whose conversion efficiency is more than 30%, developed by NREL [8]. (8) In 1995, for the growth of InAs, GaAs and InP, Buhro's *et al.* introduced a solution–liquid–solid mechanism that works on low temperature and solution–phase reactions [9]. (9) In 2000, the Nobel Prize in physics was awarded jointly to Zhores I. Alferov and Herbert Kroemer for "developing semiconductor heterostructures used in high-speed and optoelectronics" [10].

In the current decade, the important progressive research works can be pointed to as follows: (1) In 2006, in solar cell technology, a new world record was achieved with 40% efficiency in sunlight-to-electricity performance. This record was achieved by Boeing-Spectrolab and funded by the U.S. Department of Energy [11]. (2) In 2008, the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy achieved a new record in photovoltaic solar cell efficiency that converts 40.8% sunlight into electricity, where triple-junction GaInP and GaInAs semiconductor materials were used for higher potential efficiencies [12]. (3) In 2015, solar cell conversion efficiency > 45% was achieved with four-junction inverted metamorphic concentrator solar cells. It was achieved by Ryan M. France *et al.* with NREL and funded by the U.S. Department of Energy [13]. (4) In 2018, a solar cell conversation efficiency of 29.1% with its single-junction gallium arsenide (GaAs) devices was achieved by Alta Devices, a US-based specialist gallium arsenide (GaAs) PV manufacturer, and it certified by Germany's Fraunhofer ISE CalLab [14] [15]. (5) In 2018, solar cell efficiency greater than 50% was demonstrated with a six-junction inverted metamorphic multi-junction concentrator solar cell by John F. Geisz *et al.* with the National Renewable Energy Laboratory (NREL) and supported by the U.S. Department of Energy [16]. (6) In 2022, by a team of Frank Dimroth at the Center for Highly Efficient Solar Cells at Fraunhofer ISE, a new world record for solar cell energy conservation efficiency of 47.6% was achieved with a 4-junction anti-reflection layers solar cell. This record was achieved using upper tandem solar cells of GaInP, AlGaAs, and lower tandem solar cells of GaInAsP, GaInAs [17] [18]. (7) In May 2023, Xia Wang *et al.* reached to make 35.1% conversation efficient inverted metamorphic 5-junction solar cells were grown by metal organic chemical vapor deposition on the gallium arsenide substrates [19]. (8) In July 2023, Kevin L. Schulte *et al.* made single-junction GaAs solar cells with 27% efficiency, which were grown on acoustically spalled GaAs substrates [20]. (9) In August 2023, Kevin L. Schulte *et al.* got success in computational modeling and experimental testing of rear hetero-junction solar cells with a 27% efficient GaAs cell grown with Halide Vapor Phase Epitaxy (HVPE) [21] [22].

III. RESEARCH WORKS ON III-V THIN FILM COMPOUNDS FROM 2018 TO 2023

First, we can observe that the highly efficient III-V solar cells are employed in space and CPV technologies. Since III-V semiconductor materials (such as GaAs) and Germanium have lattice matching, III-V compounds are a better option than Silicon for lowering solar cell manufacture cost [23].

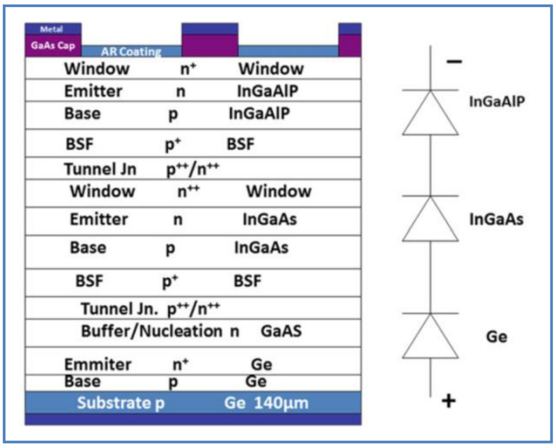

Figure 1 schematic cross-section of III-V 3-junction solar cell and diode form of it [23].

In March 2018, Mortin Johnson N. *et al.*, in the 4th International Conference on Devices, Circuits and Systems (ICDCS) at Coimbatore, India, reported that simulated single-junction multiband solar cells have utilized the full solar spectrum by multiband structured GaAs thin film. In this solar cell, the layers of GaAs materials with a 1.4 *eV* band gap and AlGaAs materials with varying band gaps from 1.42 *eV* to 2.16 *eV* have been stacked on the Silicon substrate from bottom to top. In this single junction multilayer solar cell, they obtained efficiency of 27.29% with V_{OC} of 1.076 *V*, Fill Factor (FF) of 88.702%, and device short circuit current J_{SC} of 28.6mA/cm^2. They reported that the efficiency was increased because GaAs and AlGaAs have a direct band gap; their charge carriers can directly emit the photos. This simulation work have been done with emitter thickness = 2μm, base thickness = 1.8μm, and FSF (Font Surface Field) thickness = 0.000001μm [24]. Using trimethylgallium, trimethylaluminium, trimethylindium, phosphine, and arsine as precursor's materials and diluted all these in hydrogen carrier gas by Romain Carious *et al.* in April 2018 and growth GaInP thin film. They demonstrated a 33.3% efficient 2-ternminal GaInP/GaAs/Si solar cell at 1-sun AM1.5G, thin films grown through MOVPE onto a GaAs (100) substrate at pressure 50 *mbar* and temperature changed between 500°*C* to 700°*C* [25]. The J_{SC} = 1.1mA/cm^2 and Si subcell V_{OC} is more than 690 *mV* was recorded with GaInP/GaAs top cell, which is possible due to near-bandgap absorption enhancement.

A quadruple-junction InGaP/GaAs top cell was stacked on Si bottom cell by Takeyoshi Sugaya *et al.* and first demonstrated a 2-terminal quadruple-junction III-V top solar cell fabricated on Si bottom cell by using smart track technology in June 2018. They obtained 18.5% conversion efficiency with V_{OC} = 3.3 *eV* and J_{SC} = 7.4 mA/cm^2 [26]. For smart stacking, the solid source MBE method has been used to fabricate multijunction solar cells. The J_{SC} was good and controlled by the second GaAs cell, and it can be improved by reducing the thickness of the first InGaP cell, which is the absorber layer of the solar cell. Alta Devices Company, which works in Solar and Renewable Energy Devices, got success in December 2018 to make a single-junction gallium arsenide (GaAs) solar cell with 29.1% efficiency [14] [15] [27]. Kaitlyn T. VanSant *et al.* in March 2019, fist time, have used the Hydride Vapor Phase Epitaxy (HVPE) method to replace the traditional Metal Organic Vapor Phase Epitaxy (MOVPE) method and demonstrated 4-terninal III-V/Si tandem solar cells. They reported an Al-free 4-T GaAs/Si tandem solar cell with 29% efficiency without costly deposition techniques like

MOVPE or MBE, and this cell structure is the same as the GaAs/Si tandem cell grown by the MOVPE method. Finally, with a structural optimization of GaAs top cell, they provided 31.4% efficiency [28]. Figure 2 shows the schematic layout of a tandem solar cell presented by Kaitlyn T.VanSant.

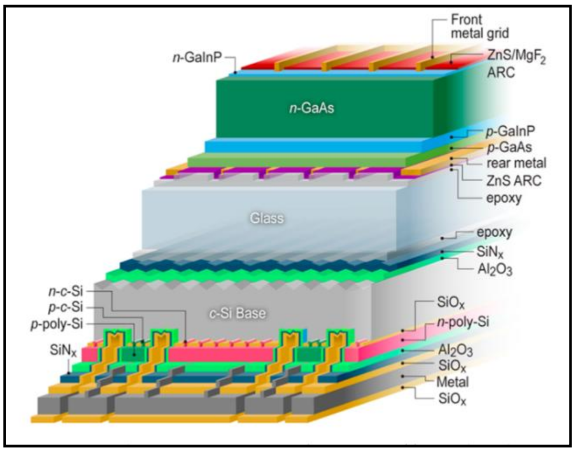

Figure 2 schematic layout of Al-free GaAs top cell with 4T GaAs/Si tandem cell [28].

To achieve both high efficiency and low cost, in April 2019, T.Nishida demonstrated high potential Ge seed layer on glass substrate for GaAs thin film solar cells. The GaAs thin film grown epitaxially at 520°*C*, provide a pseudo single crystal with orientation (111) and grain size >100μm. It provides an idea to fabricate high-efficiency III-V thin film solar cell on glass substrate with low- cost [29]. In June 2019, William E. McMohan *et al.* fabricated thin III-V solar cell on Ni film with depositing a thin Ni film on both rigid and flexible supports via electroless deposition method at low temperature 78°C. Electroless Ni deposition provides stress-free, uniform and structural support to the cell. We know that the high temperature changes with metals can stress and fracture the III-V solar cell, but it seen in the results that the cell does not damage during process at temperature under 100°*C* [30]. By a thermal stable tunnel junction, in November 2019, Shizhao Fan *et al.* presented 20.0% efficiency NREL-certified epitaxial $GaAs_{0.75}P_{0.25}$/Si double-junction tandem cell. They also demonstrated a $GaAs_{0.75}P_{0.25}$-filtered Si bottom cell of 7.78% efficiency and $GaAs_{0.75}P_{0.25}$ single – junction top cell of 16.5% efficiency with developed short-circuit current densities [31]. They have grown GaAsP/Si double-junction cells on GaP/Si (100) templates by MBE method.

In April 2020, six-junction solar cell made up alloys of III-V semiconductor materials demonstrated by John F. Geisz *et al.* They obtained, 47.1% solar energy conversion efficiency for six – junction inverted metamorphic structure at 143 Suns concentration and a 1-Sun global efficiency of 39.2% achieved for a variation of this structure. This six-junction was obtained by stop phase segregation in meta-stable quaternary alloys and minimizing threading dislocations in lattice mismatched of alloys. The III-V layer structures were grown by Metal Organic Vapor Phase Epitaxy (MOVPE) method, where growth temperature was taken between 550°*C* to 750°*C* and controlling quality and doping of alloy growth [32]. With using TiO_2 material for front nanostructure and high band gap AlGaAs material for back of the cell, Jeronimo Buencuerpo *et al.* in April 2020, presented adapted light trapping strategy of front and back photonic transparent material crystals on outer of the cell with 300 *nm* GaAs absorber to enhance optically thick nature of the solar cell. The back metallic mirror and dielectric spacer added to decrease absorption on the metal and achieved J_{SC} = 29.6 mA/cm^2 [33]. In June 2020, David Lackner *et al.* presented a GaInP/GaAs/Si wafer-bonded 3-junction 2-terminal solar cell of 34.1% efficient with AM1.5G. By using GaInP rear-heterojunction, V_{OC} = *39 mV* and J_{SC} = 1.1 mA/cm^2 have been achieved [34]. To increase V_{OC} and decrease absorption losses in the GaAs bonding layer enhanced the band gap of middle cell by adding Al into the GaAs material and the high current mismatch increase the Fill Factor to 86.4%. Figure 3 shows layout of 3-junction solar cell which is reported by Devid Lackner *et al.* in June 2020.

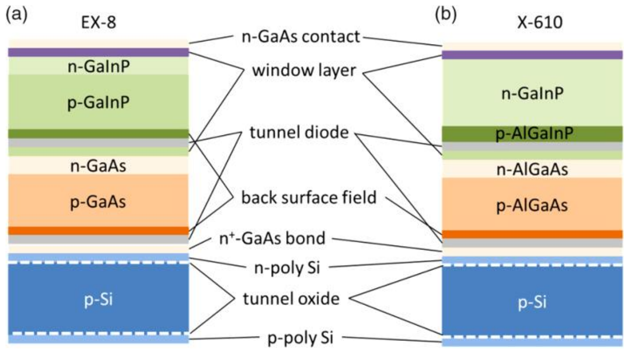

Figure 3 schematic layout of two 3-junction devices *(a)* EX-8 device with GaInP and GaAs absorber. *(b)* X610 device with GaInP rear-heterojunction and AlGaAs middle cell [34].

To fabricate a high efficiency multi-junction solar cell in thin film technology, Brandon Hagar *et al.* presented a new concept with a low cost and low temperature approach in September 2020. This was based on the inter-metallic bonding (IMB) approach of indium metal deposited on the solar cells, which removes the lattice mismatch and tunnel junction limitations, and allows each cell with patterned contacts to develop multijunction solar cells [35]. With this technique, any commercial off-the-shelf solar cells can be demonstrated, and they demonstrated GaAs/Si two and three-terminal solar cells. The GaAs top cell was grown by the MOCVD method and cleaved on *n*-GaAs substrates. The IBM approach allows integrating dissimilar material and its compounds to combine and presents flexibility in current matching. This approach with photon recycling may also be employed to increase V_{OC} between the top cell and the bottom cell. In November 2020, Vidur Raj *et al.* designed an ultrathin InP solar cell using carrier elective contacts and increased the efficiency up to 22*%* of heterojunction solar cells. At 280 *nm* thickness of InP, high J_{SC}>28 *mA/cm*^{2} achieved with enhanced anti-reflective coating and metal back reflector. They reported that with a preserved surface recombination velocity fewer than 10^5 *cm/s*, a bulk lifetime of InP requires greater than 2 *nano-second*, which provides high efficiency for ultrathin solar cells [36].

A New generation of GaInP/GaAs/Si 3-junction solar cells on Si bottom cells with 25.9% conversion efficiency with AM1.5G was presented by Markus Feifel *et al.* in March 2021 [37]. By the use of $Al_xGa_{1-x}As_yP_{1-y}$, they increased the band gaps of buffer layers that increase the transmittance in the range between 670 *nm* and 870 *nm*, and it increased J_{SC} from 10.0 *mA/cm*^{2} to 12.2 *mA/cm*^{2} in the IV generation 3-junction solar cells. Buffer has been made of $Al_xGa_{1-x}As_yP_{1-y}$ consisting of 14 layers of thickness of 160 *nm*, grown by the MOVPE to decrease optical losses at the surface. All cells have been coated by Ta_2O_5/MgF_2 antireflective coating (ARC). In June 2021, employing a mechanical stacking technique to bond a GaInP/GaAs 2-junction top subcell to a poly-Si bottom subcell, Ray-Hua Horgn *et al.* made a GaInP/GaAs/Poly-Si 3-junction solar cell. They found that this cell absorbs light of wavelength between 300 *nm* to 800 *nm*. This solar cell has 24.5*%* efficiency for GaInP/GaAs/Poly-Si 3-junction solar cell with V_{OC} = 2.68 *V*, J_{SC} = 12.39 *mA/cm*^{2} and FF = 73.8*%* [38]. In June 2021, Jana Wulf *et al.* demonstrated high conversion efficient III-V based GaAs solar cells via patterned direct rear side plating and epitaxial lift-off. The homogeneity of direct plating is crucial for the stability of the process, which enables low-cost rear side metal deposition and fast lift-off time [39].

For the first time, the III-V tandem solar cell has been fabricated through mechanical stack technology using hydride Vapor Phase Epitaxy (HVPE) method by Yasushi Shoji *et al.* in August 2021. As a bonding mediator, the Pd nanoparticles have been used, and by bonding the GaAs solar cell with the InGaAs solar cell, a GaAs/InGaAs tandem solar cell was fabricated, where GaAs cells were grown through the HVPE method and InGaAs cells were grown through the MOVPE method and achieved 22.6*%* light conversion efficiency [40]. In September 2021, Daniel L. Lepkowski *et al.* fabricated a monolithic epitaxial, 2-junction, 2-terminal III-V GaAsP/Si tandem solar cell of 23.4*%* efficiency, grown by the Metal Organic Chemical Vapor Deposition (MOCVD) method using an ex-situ produced Si subcell with B-diffused BSF [41]. The 23.4*%* efficiency at AM1.5G has been certified by NREL. To improve efficiency, they used voltage and current losses included in threading dislocations, which reduce the dislocation density. Furthermore, this group developed low TDD GaAs/Si substrates that enhanced J_{SC} and Fill Factor (FF) without losing V_{OC}, which enable GaAsP/Si tandem solar cells with almost 27% efficiency [42]. In November 2021, Patrick Schygulla *et al.* demonstrated a 35.9% efficient two-terminal wafer-bonded III-V/Si triple-junction solar cell with AM1.5g spectrum by adapting the III-V top structure [43]. Figure 4 shows a schematic model of a 3-juncton solar cell reported by Patrick Schygulla. This 35.9 % efficiency was achieved by two factors; (i) as an absorber, a GaInAsP thin film was integrated in the middle of the cell, which increased the open circuit voltage Voc = 5 *mV* and (ii) to increase the short circuit current, improved the current matching of all sub-cells. With this and an upright grown structure, they achieved V_{OC} = 3.248 *V*, J_{SC} = 13.1 mA/cm^2 and FF = 84.3% of proposed solar cell. They suggested that in the process of upright structures, additional bonding steps are required, which decrease the homogeneity of cell performance across the wafer. Using the MOVPE method, the III-V top junction solar cells were grown on the GaAs wafers as substrates. As the bottom cell, Si cell was used. For III–group elements, precursors' trimethylgallium (TMGa), trimethylaluminium (TMAI) and trimethylindium (TMIn), and for V–group precursors' phosphine (PH_3) and arsine (AsH_3) were used. For *n*-type absorber layers, the silane (SiH_4) and p-type absorber layers, dimethylzinc (DMZn) were used as doping agent precursors. At water surface temperatures from 550°*C* to 680°*C*, epitaxial growth was performed.

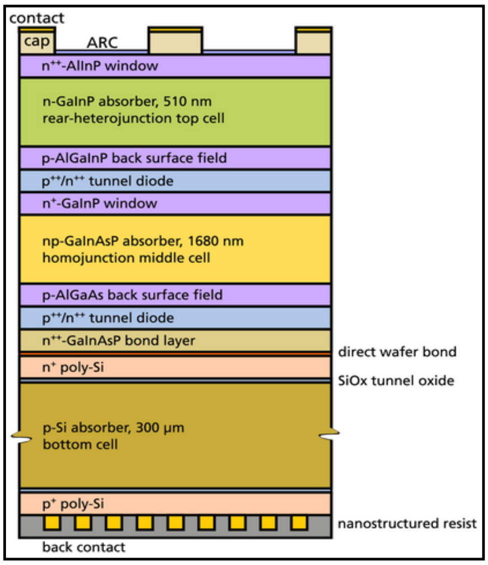

Figure 4 schematic diagram of layer stack of III-V/Si (GaAs/Si based) triple-junction solar cell [43].

Using a metal wafer bonding and epitaxial lift-off process, first time GaAa/Si thin film solar cells have been demonstrated by Seungwan Woo *et al.* in January 2022 and found 10.6% 1-Sun efficiency without anti-reflection coatings. This idea suggests to fabricate low cost wafer bounded III-V multi-junction solar cells on large range [44]. For the growth of all samples, molecular beam epitaxy (MBE) method was used, and for the epitaxial lift-off (ELO) process, a 50 *nm* aluminum arsenide (AlAs) was used as a sacrificial layer between *p*-GaAs contact layer and 100 *nm* LT-GaAs butter. To remove thermal cracks between GaAs and Si layers and reduce threading dislocation density, InGaAs single insertion layer and high quality 2.1 µm thick GaAs butter were used that provided the excellent homogeneity of the material's optical property. They suggested that the improved GaAs solar cell structure with back-surface filed layer and InGaP window layer, will enhance the efficiency of the Cells.

In March 2022, Julia R. D'Rozario *et al.* examined the integrated texture back surface reflectors (BSR) with 01 *eV* InGaAs thin film solar cells, including surface treatments using the reactive ion etching (RIE) process. This combination showed the enhancement in the short-circuit current density than flat BSR, and the lifetime enhancement factors for the flat and RIE-BSR were 2.4 and 3.6, respectively. These textured reflectors increase the photon path length and improved photon absorption to achieve highly efficient space solar cells [45]. In May 2022, Jingjing Xuan *et al.* proposed a module manufacturing scheme based on resistance welding and lamination technology to encapsulate lightweight and flexible III-V solar cells. For the lamination ethylene octane copolymer, polyimide and ethylene-tetrafluoroethylene were used and measured 34.4% photoelectric conversion efficiency with V_{OC} = 3.04 *V* for the flexible solar cell and 32.7% with 469 gm^{-2} weight density for the flexible module [46].

In the 2nd International Tandem PV Workshop organized in May 2022 at Freiburg, Germany, the researchers of the Fraunhofer Institute for Solar Energy Systems (ISE) presented 47.6% conversion efficient quadruple solar cells at 665 times the sun concentration. This milestone has been achieved by using 4-layer anti-reflective coating layers at the center, which reduces resistance losses and reflection from the front of the cells as well as showing sensitivity between 300 and 1780 *nm* spectral ranges [17]. In June 2022, Masafumi Yamaguchi *et al.* reported that the External Radiative Efficiency (ERE) values of GaAs single-junction solar cells have been improved and realized by photon recycling with some improvement in technology. Also, to improve in ERE of III-V multi-junction and III-V/Si tandem solar cells, improvement in ERE of sub-cells is required. The ERE of III-V multi-junction and III-V/Si tandem solar cells is a function of the number of junctions, so the ERE decreases as the number of junctions increases. Due to the oxygen-related non-radiative recombination center, ERE of Al contained a wide sub-cell layer (like AlGaInP, AlGaAs) to be decreased [47].

The hole selective III-V Solar cells have been demonstrated for the first time by Tuomas Haggren *et al.* in November 2022, with a solar conversion efficiency of 13.4%, using oxygen assisted Copper Iodide (CuI) on *i*-GaAs. The incorporated oxygen on CuI enhances the hole selectivity of the solar cells and improves the conversion efficiency of the cell with V_{OC} of near 1.0 *V*. With significant impact and a low cost crystal growth method, it enables full carrier-selective architectures and reduces the manufacturing complexities of cells [48]. Then, in January 2023, they demonstrated a multilayer epitaxial lift-off process with epitaxial strain. After the lift-off, the films remained of good integrity without external support and demonstrated a cm-scale solar cell. They suggested that a scalable multilayer lift-off process can reduce 4- to 6-cost effect compared to a single-layer epitaxial lift-off process [49]. In March 2023, Wu Xiaoxu *et al.* to find out the long-term stability tested unencapsulated flexible GaInP/GaAs/InGaAs thin film solar cells at 85°*C* damp heat for more than 1000 *hours* and 420 thermal cycling between –60°*C* and 75°*C*, respectively. The few decreases in V_{OC}, enhance the recombination and the reverse saturation current. These performances were good and showed the stable and reliable device fabrication art. First, in the GaAs substrate, the GaInP lattice matched subcells were deposited, then lattice mismatched InGaAs subcell was grown. To grow these solar cells, metal-organic chemical vapor deposition (MOCVD) was used, and the process that had been used is shown in Figure 5 [50].

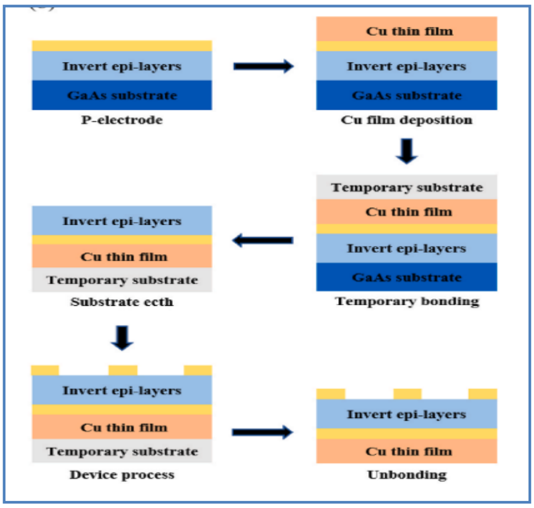

Figure 5 the flow chart of process for the flexible GaInP/GaAs/InGaAs solar cells [50].

D.V. Prashant *et al.* in March 2022 proposed a simple and effective design of a GaAa thin film solar cell with improved photo-generation in the active layer by using oxide as a front reflector and metal as a back reflector, and they achieved a power conversion efficiency of 21% for the proposed device [51]. In June 2023, Tadas Paulauskas *et al.* are the first researchers who assess and report bismuth-containing triple-junction solar cells with GaAsBi absorbers, where to increase the efficiency, Germanium (Ge) is replaced with 1.0 *eV* GaAsBi subcell on GaInP/InGaAs/Ge solar cells. To add crystalline GaAsBi absorber, a stem-graded InGaAs buffer layer is used. The molecular beam epitaxy (MBE) method is used to grow solar cells and achieved 19.1*%* conversion efficiency at AM 1.5 G spectrum found V_{OC} = 2.51 *V* and J_{SC} = 9.86 mA/cm^2 [52]. Using an unfocused Nd:YAG laser pulse laser, to separate single-crystalline multilayers from the growth substrate GaAs, which enhances the performance of the solar cell and makes reuse of wafer. This work, done by Benjamin A. Reeves *et al.* in June 2023, demonstrated 17.4*%* power conversion efficiency of the solar cells with V_{OC} = 1.07 *V* with no anti-reflection coating and using AM1.5 direct [53]. For it, they first synthesized standard III-V thin film through MOVPE, then grown a multilayer inverted rear heterojunction III-V photovoltaic cell using GaAs as substrate, *n*-$Ga_{0.97}In_{0.03}As_{0.99}N_{0.01}$ as the front contact layer, *n*-$Al_{0.52}In_{0.48}P$|$Ga_{0.49}In_{0.51}P$ as the window layers, *n*-GaAs as the absorber, *p*-$Ga_{0.49}In_{0.51}P$ as the heterojunction base, and *p*-$Al_{0.3}Ga_{0.7}As$ as the rear contact layer. For the crystal ejection, they first polished the single-side of the substrate GaAs, which produce a specular surface that is protected during laser processing. Then the laser pulse creates the characteristic spatial fluence profile with pulse 1.1± 0.1 *J* energies that ejected the single crystalline multilayer.

Kevin L. Schulte *et al.* presented both the experimental and computational study of III-V heterojunction photovoltaic cells in September 2023 and reported the impact of the emitter doping and emitter bandgap on device efficiency. They achieved maximum efficiency of 27*%* (certified by the NREL's Cell and Module Performance Team) in a GaAs/GaInPAs heterojunction solar cell by pushing the junction depletion region into the wider band gap. To grow the solar cells, they used the HVPE method, and for the device modeling, they used the AFORS-HET open access software package. [54]

IV. CONCLUSION

It is evident that thin films of III-V semiconductors are essential in the thin film solar cell technology. Several research teams are working continuously to enhance the efficiency of III-V semiconductor thin film solar cells. The governments and companies involved in this field have supported their efforts, and companies have also embraced their ideas, suggestions or inventions to encourage the use of solar energy. We can see that from 2018 to 2023, the highest solar energy conversion efficiency of 47.6*%* has been achieved by using 4-junction anti-reflection layers in the solar cells. In this duration, smart track technology has been used and demonstrated a 2-terminal quadruple-junction III-V solar cell. Additionally, to increase the efficiency of the solar cells, the MOVPE method and the Hydride Vapor Pulse Epitaxy (HVPE) method have been combined. To obtain higher efficiency and decrease manufacturing costs, Ni film is utilized as a substrate to increase efficiency and lower manufacturing costs. From 2018 to 2023, a variety of processes and techniques were used to increase the power conversion efficiency of the solar cells from 29% to 47.6%. These included the use of thermally stable tunnel junctions, light trapping strategies, improvements in homogeneity, mechanical stack technology, reduction work in dislocation density, adoption of III-V top structures, improvements of the current matching of subcells, metal wafer bonding, and epitaxial lift-off processes. Additionally, surface treatments by reactive ion etching, resistance welding and lamination technology, external radiative efficiency (ERE) improvement by photon recycling, epitaxial lift-off process with epitaxial strain, use of oxide as front reflector and metal as back reflector, use of laser process to separate layers, push the junction depletion region, etc. have been employed. Numerous techniques such as HVPE, MOVPE, MBE and MOCVD have been primarily employed and made a range of solar cells such as GaAs multiband structural solar cell, 2-terminal quadruple-junction top solar cell, Al free 4-terminal III-V/Si tandem solar cells, GaAsP/Si double-junction cell on GaP/Si substrate, 6-junction solar cell, GaInP/GaAs/Si wafer-bonded 3-junction 2-terminal solar cell, ultrathin InP solar cell, GaInP/GaAs/Si 4^{th} generation 3-junction solar cell, GaAs/InGaAs tandem solar cell, monolithic epitaxial 2-junction 2-terminal GaAsP/Si tandem solar cell, two-terminal wafer-bonded III-V/Si triple-junction solar cell, bismuth –containing triple junction GaInP/InGaAs/GaAsBi solar cell, GaAs/GaInPAs heterojunction solar cell, hole selective III-V solar cell, etc. have been demonstrated.

It is clear that a multilayer heterojunction solar cell with multi-bandgaps absorbs the photons of various energies in a wide spectrum region. So, on the basis of the absorption of photons in the spectrum region, multilayer thin films in particular order may be used to enhance the efficiency and stability of photovoltaic solar cells. It is also suggested that there should be more work in the low-cost methods such as sol-gel, chemical both deposition, and SILAR methods with the above improvement processes.

V. FUTURE RESEARCH SCOPE

To enhance light absorption efficiency of III-V thin film solar cells, actively working to optimize material properties such as bandgap mechanics, reducing recombination losses, exploring heterostructures, and carrier collection. For better utilization of the tandem solar cells, stacking multiple subcells with different bandgaps will receive more attention from researchers and industries. In tandem solar cells, the combination of III-V thin films with silicon solar cells may achieve high efficiency, so researchers should develop methods to integrate III-V thin film layers onto silicon substrates. Also, researchers should work to improve crucial qualities of thin films, such as uniformity and thickness control. We know that surface defects and carrier lifetime significantly impact the cells performance, so passivation techniques should be compulsory to reduce recombination at the surface and improve carrier lifetime. To enhance light trapping and absorption, many researcher groups are working on nanostructured surfaces, textured interfaces, and antireflection coatings; they should develop photon management strategies to boost overall efficiency. To improve the stability and reliability, researchers will work on degradation mechanisms and develop robust encapsulation methods. Cost reduction is one important aspect of the solar cells, so to reduce the cost of production of solar cells, innovative growth techniques and scalable manufacturing processes will be required.

DECLARATION OF COMPETING INTEREST

Authors declared that there is no conflict of interest and values for all work shown here have been given to actual and referenced persons.

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