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

Lekhram Hirwani
Lt. D.B.T. Govt. College
Gurur, Chhattisgarh, India
lekhramhirwani@gmail.com

Vani Chandrakar
Govt. Nagarjuna PG College of Science
Raipur, Chhattisgarh, India
vani3224@gmail.com

Goverdhan Yadu
Govt. Rajiv Lochan College
Rajim, Chhattisgarh, India
goverdhany@gmail.com

A. Oudhia
Govt. Nagarjuna PG College of Science
Raipur, Chhattisgarh, India

ABSTRACT

The III – V semiconductor based solar cell are catching worldwide attention in solar power generation and playing crucial role in nation's scientific and economical growth. These materials and its compounds are used mostly in the solar cell because of direct band gap, high optical absorption coefficient, higher conversion efficiency and chemical stability. A short reviewing the history of III – V semiconductor thin film technology in research and commercialization are discussed. On the other hand, the reviewing on important inventions and thin film solar cell designs from 2018 to 2023 are discussed. Various Processes, technologies and preparation method used in this duration to enhance the efficiency of solar cell are also discussed. The new concerns related to flexible solar cell, Al free solar cell, Ni and Bi used solar cell and hole selection solar cell are reviewed. How the photovoltaic parameters such as V_{OC}, J_{SC}, FF and power conversion efficiency are changed for prepared solar cell under different conditions are highlighted.

Keywords: Thin film, Solar Cell, III – V thin film.

I. INTRODUCTION

Thin film Solar Cells are the devices that made by the photovoltaic materials to convert the light energy (especially from Sunlight) to the electrical energy. Photovoltaic material deposited on the substrate such as glass, quartz, semiconductors, plastic, ceramics, mica, polymers, metals alloys, insulators and organic materials, which are used on solar cell is absorbing 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 few nanometers to the few micrometers which are based on solar cell application. Work on the thin film solar cell originally began by the researchers from the Institute of Energy Conservation at University of Delaware, United State of America in 1970s, but there was not big valuable output until the 1980s. With two decade progress, in 2000, the Nobel Prize in physics is given to the Zhores alferov's team from the Loffe Institute on his work created first gallium arsenide (GaAs) heterostructure solar cell, which efficiency over then 26% in laboratory environment provide more opportunity on robotic work [1]. Photovoltaic solar cell technology, earlier used is based on the single and multi-junction silicon and currently used thin layers materials such as binary materials - GaAs, CdTeb, ternary InGaAs, CIGS (copper indium gallium selenide) and quaternary materials – AlInGaP, InAsSbP, which higher ionicity increase the band gap than less ionic compounds [2]. Light conversion efficiency of single-junction thin film GaAs solar cell reaches to more than 29% [3]. In the future, innovative and more efficient thin film such as dye-sensitized, perovskite, CZTS, organic and quantum dot, which leads less environmental impacts, human toxicity and heavy-metal emissions, will be used on the solar cell and space technology [4].

Group III – V semiconductor materials are basic and its compounds are much effective for modern microelectronics because they show the superior properties for high energy conversion efficiency than other group materials and its compounds. In addition, Group III – V thin film solar cells have more radiation hardness and reduced required area by three order magnitude compare than other modules, so it opens new window for high energy solar cells and become cost-efficient [5]. This paper reports the progress and current research works in the III – V semiconductor thin film materials and compounds in the field of renewable energy sources and photovoltaic solar cells. In the first part, summarized the milestone's progressive research works on important III – V semiconductor thin film compounds up to 2023. In the second part, described the research works from 2018 to 2023 on the III – V semiconductor thin film materials and compounds. Then we will conclude and give future research scope on it.

II. THE MILESTONES PROGRESS IN IMPORTANT III – V THIN FILM COMPOUNDS TILL 2023

Some Milestones of progress in the important III – V thin film compounds are in the following –

1. In 1950, firs solar cell produced by Bell Labs for space activities.
2. In 1970, first highly effective GaAs heterostructure thin film solar cell was introduced by the some researchers of institute of energy conservation in the United state [6].
3. In 1972, established world's first laboratory for the photovoltaic research and first time developed thin film photovoltaic solar cell.
4. In 1974, Florida Solar Energy Center was started by Florida Energy Committee and the Florida State Legislature [7].
5. In 1981, first time demonstrated more than 9% efficient thin film solar cell using copper indium sulfide ($CuInS_2$) and Cadmium Sulfide (CdS) materials.
6. In 1986, the world first commercial thin film power module 'G-4000' made by ARCO Solar.
7. In 1994, GaInP/GaAs was the two-terminal concentrator solar cell which conversation efficiency is more than 30% developed by NREL [8].
8. In 1995, for the growth of InAs, GaAs and InP, Buhro's *at al.* introduced a solution – liquid – solid mechanism, which work on low temperature and solution – phase reactions [9].
9. In 2000, Nobel Prize in the physics was awarded jointly to the Zhores I. Alferov and Herbert Kroemer to "developing semiconductor heterostructures used in high speed and optoelectronics" [10].
10. In 2006, In Solar Cell Technology, New world record achieved with 40% efficiency in sunlight-to-electricity performance. This record achieved by Boeing-Spectrolab and funded by U.S. Department of Energy [11].
11. In 2008, National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy achieved new record in photovoltaic solar cell efficiency that converts 40.8% sunlight into electricity, where triple-junction GaInP and GaInAs semiconductor materials was used for higher potential efficiencies [12].
12. In 2015, Solar Cell conversion efficiency > 45% achieved with four-junction inverted metamorphic concentrator solar cells. It was achieved by Ryan M. France at al. with NREL and funded by U.S. Department of Energy [13].
13. In 2018, a Solar Cell conversation efficiency of 29.1% with its single-junction gallium arsenide (GaAs) devices achieved by Alta Devices, a US-based specialist gallium arsenide (GaAs) PV manufacturer and it certified by Germany's Fraunhofer ISE CalLab [14] [15].
14. In 2018, solar cell efficiency more than 50% demonstrated with six-junction inverted metamorphic multi-junction concentrator solar cell by John F. Geisz *et al.* with National Renewable Energy Laboratory (NREL) and supported by the U.S. Department of Energy [16].
15. In 2022, by a team of Frank Dimroth at the Center for Highly Efficient Solar Cell at Fraunhofer ISE, a new world record for solar cell energy conservation efficiency of 47.6% achieved with a 4-junction anti-reflection layers solar cell. This record achieved using upper tandem solar cell of GaInP, AlGaAs and lower tandem solar cell of GaInAsP, GaInAs [17] [18].
16. In May 2023, Xia Wang at 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].

17. In July 2023, Kevin L. Schulte at al. made a single-junction GaAs solar cells with 27% efficiency, which grown on acoustically spalled GaAs substrates [20].
18. In August 2023, Kevin L. Schulte *at al.* got success to made 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 see that the high efficient III – V solar cells are used in the CPV and space technology where III-V compound like GaAs present better option than Germanium (it has lattice matching with III-V compounds) to reduce the cost in the solar cell fabrications [23].

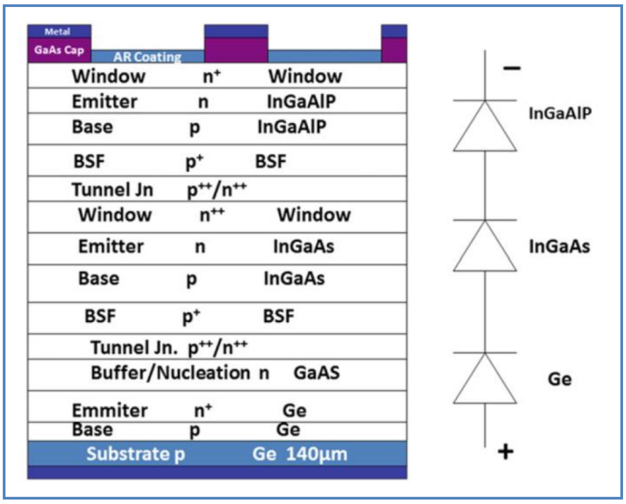

Figure 1 schematic cross-section of III – V 3-junction solar cell and diode form same solar cell [23].

In March 2018, Mortin Johnson N. *at al.* in 4th International Conference on Devices, Circuits and System (ICDCS) at Coimbatore, India, reported that simulated single junction multiband solar cell have utilized full solar spectrum by multiband structured GaAs thin film. In this solar cell, the layers of GaAs materials with 1.4*eV* band gap and AlGaAs materials with varies band gaps from 1.42*eV* to 2.16*eV* have stacked on the Silicon substrate from bottom to top. In this single junction multilayer solar cell, they obtained efficiency 27.29%, V_{OC} 1.076*V*, Fill Factor (FF) 88.702% and device short circuit current J_{SC} 28.6mA/cm^2. They reported that the efficiency was increased because GaAs and AlGaAs have direct band gap, their charge carriers can directly emit the photos. This simulation work have done with emitter thickness = 2μm and 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 *at 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, have possible due to near-bandgap absorption enhancement.

A quadruple-junction InGaP/GaAs/GaAs top cell was stacked on Si bottom cell by Takeyoshi Sugaya *at 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 more improved by reducing thickness of first InGaP cell, which is the absorber layer of the solar cell. Alta Devices Company, which is work on Solar and Renewable Energy Devices, got success in December 2018 to made single-junction gallium arsenide (GaAs) solar cell with 29.1% efficiency [14] [15] [27]. Kaitlyn T. VanSant *at al.* in March

2019 fist time using Hydride vapor Phase Epitaxy (HVPE) method to replacing traditional Metal Organic Vapor Phase Epitaxy (MOVPE) method and demonstrated 4-terminal III – V/Si tandem solar cell. They reported Al free 4-T GaAs/Si tandem solar cell with 29% efficiency without costly deposition techniques like as MOVPE or MBE and this cell structure has same like as GaAs/Si tandem cell grown by MOVPE method. Finally, with a structural optimization of GaAs top cell they provide 31.4% efficiency [28]. Figure 2 shows schematic layout of tandem solar cell presented by Kaitlyn T.VanSant.

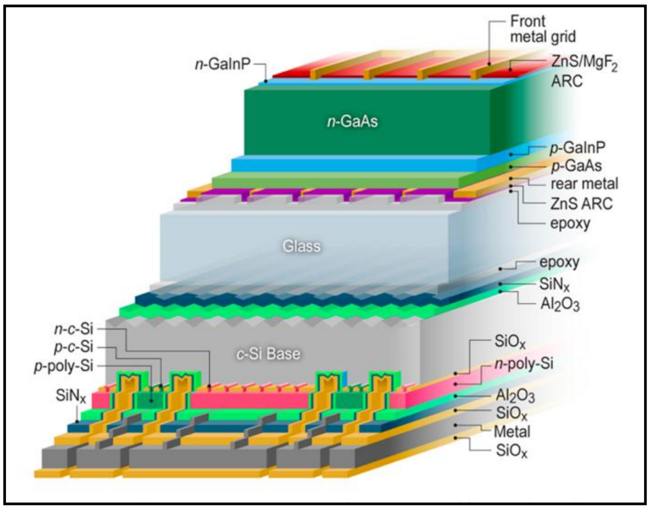

Figure 2 Show schematic layout of Al free GaAs top cell with 4T GaAs/Si tandem cell reported by Kaitlyn T. VanSant *at al.* [28].

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 >100*μm*. 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 *at 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 *at 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 *at 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 *at 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 *at 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 *at al.* in June 2020.

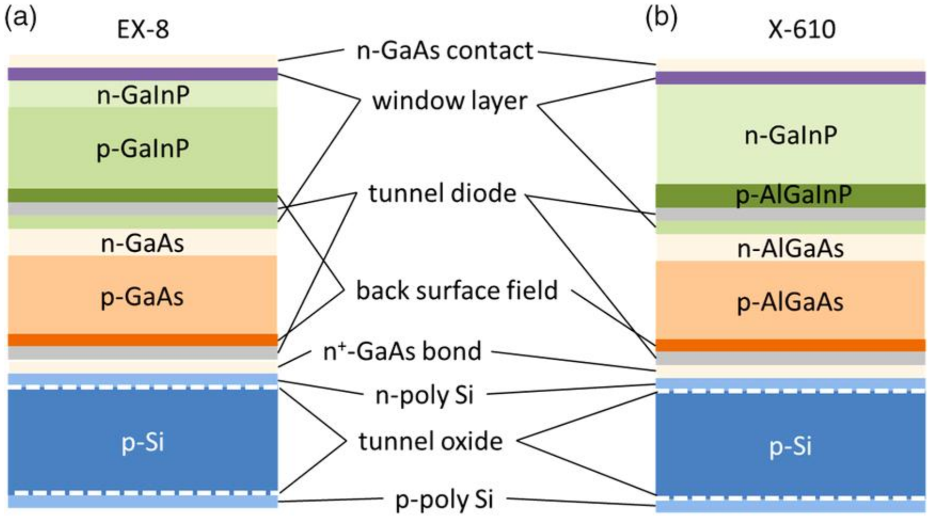

Figure 3 Show schematic of two 3-junction devices *(a)* EX-8 device with GaInP and GaAs absorber. *(b)* X610 device with GaInP rear-heterojunction and AlGaAs middle cell [34].

To fabricate a high efficiency multi-junction solar cell in thin film technology, Brandon Hagar *at al.* in September 2020 presented a new concept with low cost and low temperature approach. This was based on the inter-metallic bonding (IMB) approach of indium metal deposited on the solar cells, which remove the lattice mismatch and tunnel junction limitations, 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 MOCVD method and cleaved on *n*-GaAs substrates. The IBM approach allows integrating dissimilar material and its compounds to combine and presented flexibility in current matching. This approach may also be employed photon recycling to increase V_{OC} between top cell and bottom cell. In November 2020, Vidur Raj *at al.* design a ultrathin InP solar cell using carrier elective contacts and increased the efficiency upto 22*%* of heterojunction solar cell. At 280 *nm* thickness of InP, high J_{SC} > 28 nm/cm^2 achieved with enhanced anti-reflective coating and metal back reflector. They reported that with preserve surface recombination velocity fewer than 10^5 *cm/s*, a bulk lifetime of InP require greater than 2*nano-second*, which provides high efficiency for ultrathin solar cell [36].

New generation of GaInP/GaAs/Si 3-junction solar cells on Si bottom cell with 25.9% conversion efficiency with AM1.5G presented by Markus Feifel *at 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* to 870 *nm* and it increase J_{SC} from 10.0 mA/cm^2 to 12.2 mA/cm^2 in the IV generation 3-junction solar cell. Buffer has made of $Al_xGa_{1-x}As_yP_{1-y}$ consisting 14 layers of thickness of 160 *nm*, grown by MOVPE and decrease optical losses at the surface, all cells have been coated by Ta_2O_5/MgF_2 antireflective coating (ARC). In June 2021, with employing a mechanical stacking technique to bond a GaInP/GaAs 2-junction top sub cell to a poly-Si bottom subcell Ray-Hua Horgn *at al.* made a GaInP/GaAs/Poly-Si 3-junction solar cell. They found that this cell absorb 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 *at 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].

First time, the III-V tandem solar cell have been fabricated through mechanical stack technology using hydride vapor phase Epitaxy (HVPE) method by Yasushi Shoji *at al.* in August 2021. As a bonding mediator, the Pd nano-particles have been used and by bonding the GaAs solar cell with the InGaAs solar cell

GaAs/InGaAs tandem solar cell fabricated, where GaAs cell grown through HVPE method and InGaAs cell grown through MOVPE method and achieved 22.6% light conversion efficiency [40]. In September 2021, Daniel L. Lepkowski *at al.* fabricated a monolithic epitaxial, 2-junction, 2-terminal III- V GaAsP/Si tandem solar cell of 23.4% efficient, grown by Metal Organic Chemical Vapor Deposition (MOCVD) method using an ex-situ produced Si sub cell with B-diffused BSF [41]. The 23.4% efficiency at AM1.5G has certified by NREL. To improve efficiency using voltage and current losses included in threading dislocations which reduce the dislocation density. Furthermore, this group developed a low TDD GaAs/Si substrates that enhanced J_{SC} and Fill Factor (FF) without losing V_{OC}, which enable GaAsP/Si tandem solar cell with almost 27% efficiency [42]. In November 2021, Patrick Schygulla *at 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 schematic model of 3-juncton solar cell reported by Patrick Schygulla. This 35.9 % efficiency achieved by two factors (i) As a absorber, a GaInAsP thin film integrated in the middle of cell, which increased the Open Circuit Voltage Voc = 51*mV* and (ii) To increase the Short Circuit Current, improved the current matching of all sub-cells. With this and an upright grown structure, achieved V_{OC} = 3.248 *V*, J_{SC} = 13.1 mA/cm^2 and FF = 84.3%. 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 MOVPE method, the III – V top junction solar cells were grown on the GaAs wafers as substrates. As bottom cell, Si cell was used. For III – group elements precursors' trimethylgallium (TMGa), trimethylaluminium (TMAI) and trimethylindium (TMIn), for V – group precursors Phosphine (PH3) and arsine (AsH3) 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.

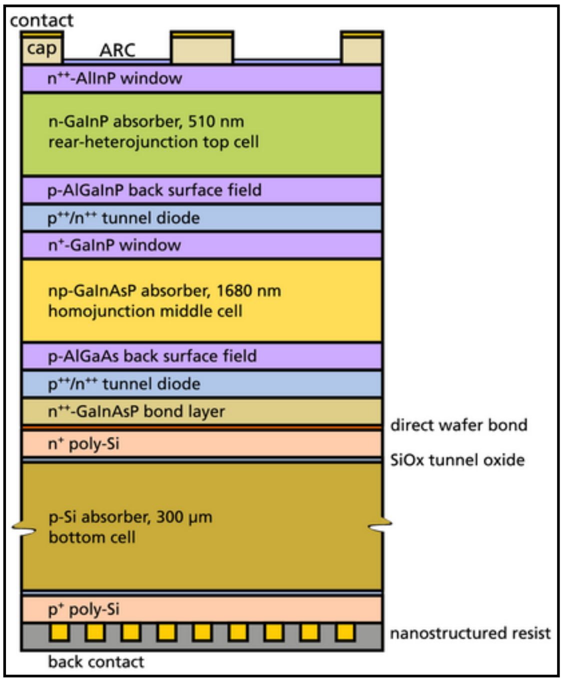

Figure 4 Show schematic layer stack of III – V/Si (GaAs/Si based) triple-junction solar cell presented by Patrick Schygulla at al. in November 2021 [43].

Using a metal wafer bonding and epitaxial lift-off process, first time GaAa//Si thin film solar cells have been demonstrated by Seungwan Woo *at al.* in January 2022 and found 10.6% 1-Sun efficiency without anti-reflection coatings. This idea provides idea for fabrication low cost wafer bounded III – V multi-junction solar cells on large range [44]. For the grown 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 and low 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 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 Cell.

With including surface treatments using reactive ion etching (RIE), Julia R. D'Rozario *at al.* examined the integrated texture back surface reflectors (BSR) with 01 *eV* InGaAs thin film solar cells in March 2022. This combination show the enhancement in the short-circuit current density than flat BSR and lifetime enhancement factors for the flat and RIE-BSR are 2.4 and 3.6 respectively. These textured reflectors increase the photon path length improved photon absorption to achieve high efficient space solar cells [45]. In May 2022, Jingjing Xuan *at al.* proposed a module manufacturing scheme based on resistance welding and lamination technology to encapsulate lightweight and flexible III – V solar cell. 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 cell at 665 times the sun concentration. This milestone has been achieved by using a 4- layer anti-reflective coating layers at the center, which reduces resistance losses and reflection from the front of the cell as well as showing sensitivity between 300 to 1780 *nm* spectral ranges [17]. In June 2022, Masafumi Yamaguchi *at al.* reported that 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 are required. The ERE of III – V multi-junction and III – V/Si tandem solar cells is a function of number of junctions, so ERE is decreases as increase the number of junctions. Due to the oxygen-related non-radiative recombination center, ERE of Al contained wide sub-cell layer (like as AlGaInP, AlGaAs) to be decreases [47].

Hole selective III – V Solar cell has been demonstrated first time by Tuomas Haggren *at al.* in November 2022 with solar conversion efficiency 13.4% using oxygen reached Copper Iodide (CuI) on *i*-GaAs. The incorporated oxygen on CuI enhance hole selectivity of solar cell and improve the conversion efficiency of the cell with V_{OC} of near 1 V. With significant impact and low cost crystal growth method it enables full carrier – selective architectures and reduce manufacturing complexities of cell [48]. Then, in January 2023, they demonstrated a multilayer epitaxial lift-off process with epitaxial strain. After the lift-off, the films remain good integrity without external support and demonstrated a cm-scale solar cell. They suggested that scalable multilayer lift-off process can be reduce 4- to 6- cost effect than single-layer epitaxial lift-off process [49]. In March 2023, Wu Xiaoxu *at 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 decrease 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 grown these solar cells, the metal-organic chemical vapor deposition (MOCVD) was used and followed process is shown in Figure 5 [50].

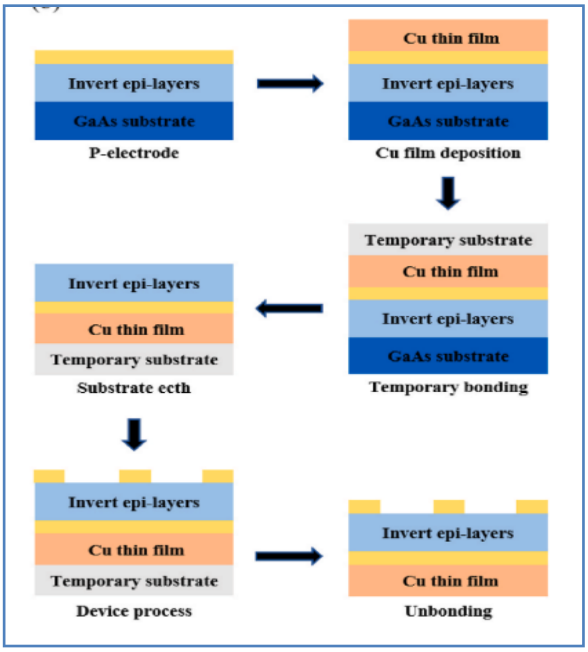

Figure 5 show the flow chart of process for the flexible GaInP/GaAs/InGaAs solar cells [50].

D.V. Prashant *at al.* in March 2022 proposed a simple and effective design of GaAa thin film solar cell with improved photo-generation in the active layer by using oxide as front reflector and metal as back reflector and they achieved power conversion efficiency of 21% for proposed device [51]. In June 2023, Tadas Paulauskas *at al.* are first researchers who assess and reports bismuth-containing triple-junction solar cell with GaAsBi absorber, where to increase the efficiency Germanium (Ge) 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 grown solar cell 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, separating single-crystalline multilayers from the growth substrate GaAs which enhance the performance of the solar cell and made reuse of wafer. This work has been done by Benjamin A. Reeves *at al.* in June 2023 and they demonstrated 17.4% power conversion efficiency of solar cell with $V_{OC} = 1.07\ V$ with no anti-reflection coating and using AM1.5 direct [53]. For this they first synthesized standard III-V thin film through MOVPE then growth multilayer inverted rear heterojunction III-V photovoltaic cell where used GaAs as substrate, n-$Ga_{0.97}In_{0.03}As_{0.99}N_{0.01}$ as front contact layer, n-$Al_{0.52}In_{0.48}P|Ga_{0.49}In_{0.51}P$ as window layers, n-GaAs as absorber, p-$Ga_{0.49}In_{0.51}P$ as heterojunction base and p-$Al_{0.3}Ga_{0.7}As$ as pear contact layer. For the crystal ejection, they first polished single-side of the substrate GaAs which produce specular surface that protected during laser processing. Then the laser pulse is created the characteristic spatial fluence profile with pulse $1.1\pm 0.1\ J$ energies that ejected the single crystalline multilayer.

Kevin L. Schulte *at al.* in September 2023 presented both the experimental and computational study of III-V heterojunction photovoltaic cell and reported the impact of the emitter doping and emitter bandgap on device efficiency. They achieved maximum efficiency 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 growth solar cells they used HVPE method and for the device modeling used AFORS-HET open access software package. [54]

IV. CONCLUSION

It is clear that III – V semiconductor thin films are dominating thin film solar cell technology. Many research groups are working continuously to enhance the efficiency of III – V semiconductor thin film solar cells. Their works have been supported by governments and companies that working on this area and companies also adopted their suggestion/invention to boost implementation of solar energy. We can see in duration 2018 to

2023, the highest solar energy conversion efficiency 47.6% has been achieved by using 4-junction anti-reflection layers in the solar cell. In this duration, smart track technology has been used and demonstrated a 2-terminal quadruple-junction III – V solar cell. Also, the Hydride Vapor Pulse Epitaxy (HVPE) method has been used with MOVPE method to enhance efficiency of solar cells. To obtain higher efficiency and decrease manufacturing cost, Ni film used as substrate. The various process and techniques such as thermal stable tunnel junction, light trapping strategy, improvement in homogeneity, mechanical stack technology, reduction work in dislocation density, adoption of III – V top structure, improvement of the current matching of sub cells, metal wafer bonding and epitaxial lift-off process, 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 separating layers, push the junction depletion region etc. have been employed in duration 2018 to 2023 and enhanced efficiency from 29% to 47.6%. There are various methods such as HVPE, MOVPE, MBE and MOCVD have been mostly used and made various 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 4th 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 multilayer heterojunction solar cell with multi-bandgap absorbs the photons of various energies in wide spectrum region. So, on the basis of absorption of photon with spectrum region, multilayer thin films in particular order may be used to enhance higher efficiency and stability of photovoltaic solar cell. It is also suggested that there should be more work in the low cost methods such as sol-gel, chemical both deposition, SILAR methods with above improvement processes.

V. FUTURE RESEARCH SCOPE

To enhance light absorption efficiency of III – V thin film solar cell actively working to optimizing material properties such as bandgap mechanics, reducing recombination losses, explore heterostructures, carrier collection. For better utilization of the tandem solar cells stack multiple subcells with different bandgaps will receive more attention of researchers and industries. In tandem solar cells, the combination of III –V thin films with silicon solar cell may achieve highly efficiency so researchers should develop methods to integrate III –V thin film layers onto silicon substrates. Also researchers should work to improving film crucial quality such as uniformity and thickness control. We know that surface defects and carrier lifetime significantly impact on the cell performance, so passivation techniques will be compulsory to reduce recombination at the surface and improve carrier lifetime. To enhance light trapping and absorption, many researcher groups are working on nano-structured surfaces, textured interfaces and antireflection coatings 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, 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.

REFERENCES

[1] M. J. Madou, *From MEMS to Bio-MEMS and Bio-NEMS: Manufacturing Techniques and Applications*. CRC Press, 2011.

[2] P. Y. Yu and M. Cardona, *Fundamentals of Semiconductors: Physics and Materials Properties*. in Graduate Texts in Physics. Berlin, Heidelberg: Springer, 2010. doi: 10.1007/978-3-642-00710-1.

[3] "Best Research-Cell Efficiency Chart." Accessed: Oct. 11, 2023. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html

[4] "Space solar power's time may finally be coming | Space." Accessed: Oct. 11, 2023. [Online]. Available: https://www.space.com/space-solar-power-research-advances

[5] A. Bett, D. Frank, G. Stollwerck, and O. Sulima, "III-V compounds for solar cell applications," *Appl. Phys. A*, vol. 69, pp. 119–129, Jan. 1999, doi: 10.1007/s003390050983.
[6] "Wayback Machine." Accessed: Oct. 25, 2023. [Online]. Available: https://web.archive.org/web/20070926195439/http://nobelprize.org/nobel_prizes/physics/laureates/2000/alferov-lecture.pdf
[7] "History," FSEC®. Accessed: Oct. 25, 2023. [Online]. Available: https://energyresearch.ucf.edu/about-us/history/
[8] K. A. Bertness, S. R. Kurtz, D. J. Friedman, A. E. Kibbler, C. Kramer, and J. M. Olson, "High-efficiency GaInP/GaAs tandem solar cells for space and terrestrial applications," in *Proceedings of 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion - WCPEC (A Joint Conference of PVSC, PVSEC and PSEC)*, Dec. 1994, pp. 1671–1678 vol.2. doi: 10.1109/WCPEC.1994.520540.
[9] T. J. Trentler, K. M. Hickman, S. C. Goel, A. M. Viano, P. C. Gibbons, and W. E. Buhro, "Solution-Liquid-Solid Growth of Crystalline III-V Semiconductors: An Analogy to Vapor-Liquid-Solid Growth," *Science*, vol. 270, no. 5243, pp. 1791–1794, Dec. 1995, doi: 10.1126/science.270.5243.1791.
[10] "The Nobel Prize in Physics 2000," NobelPrize.org. Accessed: Oct. 13, 2023. [Online]. Available: https://www.nobelprize.org/prizes/physics/2000/summary/
[11] "New World Record Achieved In Solar Cell Technology," ScienceDaily. Accessed: Oct. 25, 2023. [Online]. Available: https://www.sciencedaily.com/releases/2006/12/061206123954.htm
[12] "NREL: NREL Solar Cell Sets World Efficiency Record at 40.8 Percent." Accessed: Oct. 25, 2023. [Online]. Available: https://web.archive.org/web/20080917040839/http://www.nrel.gov/news/press/2008/625.html
[13] R. M. France *et al.*, "Design flexibility of ultra-high efficiency 4-junction inverted metamorphic solar cells," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, Jun. 2015, pp. 1–3. doi: 10.1109/PVSC.2015.7356439.
[14] T. Kenning, "Alta Devices sets GaAs solar cell efficiency record at 29.1%, joins NASA space station testing," PV Tech. Accessed: Oct. 25, 2023. [Online]. Available: https://www.pv-tech.org/alta-devices-sets-gaas-solar-cell-efficiency-record-at-29-1-joins-nasa-spac/
[15] "Alta sets flexible solar record with 29.1% GaAs cell." Accessed: Oct. 25, 2023. [Online]. Available: https://optics.org/news/9/12/19
[16] J. F. Geisz *et al.*, "Building a Six-Junction Inverted Metamorphic Concentrator Solar Cell," *IEEE J. Photovolt.*, vol. 8, no. 2, pp. 626–632, Mar. 2018, doi: 10.1109/JPHOTOV.2017.2778567.
[17] "Fraunhofer ISE entwickelt effizienteste Solarzelle der Welt mit 47,6 Prozent Wirkungsgrad - Fraunhofer ISE," Fraunhofer-Institut für Solare Energiesysteme ISE. Accessed: Oct. 26, 2023. [Online]. Available: https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2022/fraunhofer-ise-entwickelt-effizienteste-solarzelle-der-welt-mit-47-komma-6-prozent-wirkungsgrad.html
[18] "1322_PI_ISE_Weltrekord_47,6Prozent-Solarzelle.pdf." Accessed: Oct. 26, 2023. [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/presseinformationen/2022/1322_PI_ISE_Weltrekord_47,6Prozent-Solarzelle.pdf
[19] X. Wang *et al.*, "The fabrication of flexible and large-size inverted metamorphic five-junction solar cells," *Prog. Photovolt. Res. Appl.*, vol. 31, no. 10, pp. 999–1005, 2023, doi: 10.1002/pip.3704.
[20] K. L. Schulte *et al.*, "GaAs solar cells grown on acoustically spalled GaAs substrates with 27% efficiency," *Joule*, vol. 7, no. 7, pp. 1529–1542, Jul. 2023, doi: 10.1016/j.joule.2023.05.019.
[21] "showPdf.pdf." Accessed: Oct. 26, 2023. [Online]. Available: https://www.cell.com/action/showPdf?pii=S2666-3864%2823%2900338-7
[22] K. L. Schulte, J. Simon, M. A. Steiner, and A. J. Ptak, "Modeling and design of III-V heterojunction solar cells for enhanced performance," *Cell Rep. Phys. Sci.*, vol. 4, no. 9, Sep. 2023, doi: 10.1016/j.xcrp.2023.101541.
[23] J. N. Roy, "Solar Photovoltaic Technology," in *Sustainable Energy Technology and Policies: A Transformational Journey, Volume 1*, S. De, S. Bandyopadhyay, M. Assadi, and D. A. Mukherjee, Eds., in Green Energy and Technology. , Singapore: Springer, 2018, pp. 21–56. doi: 10.1007/978-981-10-7188-1_2.
[24] M. J. N., V. D. J. H., and J. M. D., "TCAD Simulation study of Single Junction GaAs solar cell," in *2018 4th International Conference on Devices, Circuits and Systems (ICDCS)*, Mar. 2018, pp. 154–158. doi: 10.1109/ICDCSyst.2018.8605170.
[25] R. Cariou *et al.*, "III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration," *Nat. Energy*, vol. 3, no. 4, Art. no. 4, Apr. 2018, doi: 10.1038/s41560-018-0125-0.
[26] T. Sugaya *et al.*, "Smart stacked InGaP/GaAs/GaAs//Si quadruple-junction solar cells," in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*, Jun. 2018, pp. 0257–0260. doi: 10.1109/PVSC.2018.8547437.
[27] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and X. Hao, "Solar cell efficiency tables (version 56)," *Prog. Photovolt. Res. Appl.*, vol. 28, no. 7, pp. 629–638, 2020, doi: 10.1002/pip.3303.
[28] K. T. VanSant *et al.*, "Toward Low-Cost 4-Terminal GaAs//Si Tandem Solar Cells," *ACS Appl. Energy Mater.*, vol. 2, no. 4, pp. 2375–2380, Apr. 2019, doi: 10.1021/acsaem.9b00018.
[29] T. Nishida, K. Moto, N. Saitoh, N. Yoshizawa, T. Suemasu, and K. Toko, "High photoresponsivity in a GaAs film synthesized on glass using a pseudo-single-crystal Ge seed layer," *Appl. Phys. Lett.*, vol. 114, no. 14, p. 142103, Apr. 2019, doi: 10.1063/1.5091714.
[30] W. E. McMahon *et al.*, "Fabrication of Thin III-V Solar Cells on Ni Films using Electroless Ni Deposition," in *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, Jun. 2019, pp. 3224–3226. doi: 10.1109/PVSC40753.2019.8980778.
[31] S. Fan *et al.*, "20%-efficient epitaxial GaAsP/Si tandem solar cells," *Sol. Energy Mater. Sol. Cells*, vol. 202, p. 110144, Nov. 2019, doi: 10.1016/j.solmat.2019.110144.
[32] J. F. Geisz *et al.*, "Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration," *Nat. Energy*, vol. 5, no. 4, Art. no. 4, Apr. 2020, doi: 10.1038/s41560-020-0598-5.
[33] J. Buencuerpo, M. A. Steiner, and A. C. Tamboli, "Optically-thick 300 nm GaAs solar cells using adjacent photonic crystals," *Opt. Express*, vol. 28, no. 9, pp. 13845–13860, Apr. 2020, doi: 10.1364/OE.391737.
[34] D. Lackner *et al.*, "Two-Terminal Direct Wafer-Bonded GaInP/AlGaAs//Si Triple-Junction Solar Cell with AM1.5g Efficiency of 34.1%," *Sol. RRL*, vol. 4, no. 9, p. 2000210, 2020, doi: 10.1002/solr.202000210.
[35] B. Hagar, I. Sayed, P. C. Colter, and S. M. Bedair, "Multi-junction solar cells by Intermetallic Bonding and interconnect of Dissimilar Materials: GaAs/Si," *Sol. Energy Mater. Sol. Cells*, vol. 215, p. 110653, Sep. 2020, doi: 10.1016/j.solmat.2020.110653.
[36] V. Raj, F. Rougieux, L. Fu, H. H. Tan, and C. Jagadish, "Design of Ultrathin InP Solar Cell Using Carrier Selective Contacts," *IEEE J. Photovolt.*, vol. 10, no. 6, pp. 1657–1666, Nov. 2020, doi: 10.1109/JPHOTOV.2019.2961615.

[37] M. Feifel *et al.*, “Epitaxial GaInP/GaAs/Si Triple-Junction Solar Cell with 25.9% AM1.5g Efficiency Enabled by Transparent Metamorphic AlxGa1−xAsyP1−y Step-Graded Buffer Structures,” *Sol. RRL*, vol. 5, no. 5, p. 2000763, 2021, doi: 10.1002/solr.202000763.

[38] R.-H. Horng, Y.-C. Kao, A. Sood, P.-L. Liu, W.-C. Wang, and Y.-J. Teseng, “GaInP/GaAs/poly-Si Multi-Junction Solar Cells by in Metal Balls Bonding,” *Crystals*, vol. 11, no. 7, Art. no. 7, Jul. 2021, doi: 10.3390/cryst11070726.

[39] J. Wulf, E. Oliva, G. Mikolasch, J. Bartsch, F. Dimroth, and H. Helmers, “Thin film GaAs solar cell enabled by direct rear side plating and patterned epitaxial lift-off,” in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, Jun. 2021, pp. 1931–1935. doi: 10.1109/PVSC43889.2021.9518788.

[40] Y. Shoji, R. Oshima, K. Makita, A. Ubukata, and T. Sugaya, “Pd-mediated mechanical stack of III–V solar cells fabricated via hydride vapor phase epitaxy,” *Sol. Energy*, vol. 224, pp. 142–148, Aug. 2021, doi: 10.1016/j.solener.2021.06.005.

[41] D. L. Lepkowski *et al.*, “23.4% monolithic epitaxial GaAsP/Si tandem solar cells and quantification of losses from threading dislocations,” *Sol. Energy Mater. Sol. Cells*, vol. 230, p. 111299, Sep. 2021, doi: 10.1016/j.solmat.2021.111299.

[42] D. L. Lepkowski *et al.*, “Recent Advances in GaAsP/Si Top Cell Enabling 27% Tandem Efficiency,” in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, Jun. 2021, pp. 1644–1646. doi: 10.1109/PVSC43889.2021.9518768.

[43] P. Schygulla *et al.*, “Two-terminal III–V//Si triple-junction solar cell with power conversion efficiency of 35.9 % at AM1.5g,” *Prog. Photovolt. Res. Appl.*, vol. 30, no. 8, pp. 869–879, 2022, doi: 10.1002/pip.3503.

[44] S. Woo *et al.*, “Growth and Fabrication of GaAs Thin-Film Solar Cells on a Si Substrate via Hetero Epitaxial Lift-Off,” *Appl. Sci.*, vol. 12, no. 2, p. 820, Jan. 2022, doi: 10.3390/app12020820.

[45] J. R. D’Rozario, S. J. Polly, R. Tatavarti, and S. M. Hubbard, “Light management for improved photon absorption in thin-film radiation-tolerant multijunction space photovoltaics,” in *Physics, Simulation, and Photonic Engineering of Photovoltaic Devices XI*, SPIE, Mar. 2022, pp. 32–37. doi: 10.1117/12.2609780.

[46] J. Xuan *et al.*, “Flexible Encapsulation and Module of Thin-Film GaInP/GaAs/InGaAs Solar Cells,” *Sol. RRL*, vol. 6, no. 8, p. 2200371, 2022, doi: 10.1002/solr.202200371.

[47] M. Yamaguchi, F. Dimroth, N. J. Ekins-Daukes, N. Kojima, and Y. Ohshita, “Overview and loss analysis of III–V single-junction and multi-junction solar cells,” *EPJ Photovolt.*, vol. 13, p. 22, 2022, doi: 10.1051/epjpv/2022020.

[48] T. Haggren, V. Raj, A. Haggren, N. Gagrani, C. Jagadish, and H. Tan, “CuI as a Hole-Selective Contact for GaAs Solar Cells,” *ACS Appl. Mater. Interfaces*, vol. 14, no. 47, pp. 52918–52926, 2022, doi: 10.1021/acsami.2c16033.

[49] T. Haggren, J. Tournet, C. Jagadish, H. H. Tan, and J. Oksanen, “Strain-Engineered Multilayer Epitaxial Lift-Off for Cost-Efficient III–V Photovoltaics and Optoelectronics,” *ACS Appl. Mater. Interfaces*, vol. 15, no. 1, pp. 1184–1191, 2023, doi: 10.1021/acsami.2c18629.

[50] X. Wu *et al.*, “Accelerated aging of unencapsulated flexible GaInP/GaAs/InGaAs solar cells by means of damp heat and thermal cycling tests,” *Heliyon*, vol. 9, no. 6, p. e16462, Jun. 2023, doi: 10.1016/j.heliyon.2023.e16462.

[51] D. V. Prashant, S. K. Agnihotri, and D. P. Samajdar, “Efficiency Enhancement in GaAs Ultra-Thin Solar Cell Using Anti-Reflection Coating,” in *2023 IEEE Devices for Integrated Circuit (DevIC)*, Apr. 2023, pp. 312–315. doi: 10.1109/DevIC57758.2023.10134780.

[52] T. Paulauskas *et al.*, “Performance assessment of a triple-junction solar cell with 1.0 eV GaAsBi absorber,” *Discov. Nano*, vol. 18, no. 1, p. 86, Jun. 2023, doi: 10.1186/s11671-023-03865-x.

[53] B. A. Reeves, M. A. Steiner, T. E. Carver, Z. Zhang, A. M. Lindenberg, and B. M. Clemens, “Pulsed laser ejection of single-crystalline III-V solar cells from GaAs substrates,” *Cell Rep. Phys. Sci.*, vol. 4, no. 6, p. 101449, Jun. 2023, doi: 10.1016/j.xcrp.2023.101449.

[54] K. L. Schulte, J. Simon, M. A. Steiner, and A. J. Ptak, “Modeling and design of III-V heterojunction solar cells for enhanced performance,” *Cell Rep. Phys. Sci.*, vol. 4, no. 9, p. 101541, Sep. 2023, doi: 10.1016/j.xcrp.2023.101541.