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A Brief Study on the Fabrication of III-V/Si Based Tandem Solar Cells

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ABSTRACT: Silicon (Si) solar cells are the most successful technology which are ruling the present photovoltaic (PV) market. In that essence, multijunction (MJ) solar cells provided a new path to improve the state-of-art efficiencies. There are so many hurdles to grow the MJ III-V materials on Si substrate as Si with other materials often demands similar qualities, so it is needed to realize the prospective of Si tandem solar cells. However, Si tandem solar cells with MJ III-V materials have shown the maximum efficiency of 30 %. This work reviews the development of the III-V/Si solar cells with the synopsis of various growth mechanisms i.e hetero-epitaxy, wafer bonding and mechanical stacking of III-V materials on Si substrate. Theoretical approaches to design efficient tandem cell with an analysis of state-of-art silicon solar cells, sensitivity, difficulties and their probable solutions are discussed in this work. An analytical model which yields the practical efficiency values to design the high efficiency III-V/Si solar cells is described briefly.

Key words: III-V solar cell, Si substrate, Tandem solar cell, Multijunction

1. Introduction

Silicon-based technologies have always been dominant in the photovoltaic (PV) industry with a market share exceeding 95%[1]. A drastic reduction in fabrication cost of Si solar cell irrespective of efficiency improvements has been the key factor behind this. However, improvements in mass production technologies led to a strong and cheap PV industries, which started being competitive with conventional energies. While nowadays, efforts are still ongoing to improve Si cells efficiency by minimizing the shadow losses due to front contacts[2], reducing the surface recombination losses[3] and exploring new technologies[4] to achieve beyond maximum theoretical efficiency. The most recent record reported is of 26.7 % under AM1.5G[5], approaching towards 29% theoretical maximum efficiency stated in 1961 by Shockley and Queisser[6]. In order to achieve significantly higher efficiencies, the most practical approach in practice is the tandem cell. Tandem cells provide the best-known example of such high-efficiency approaches, where efficiency can be increased merely by adding more cells of different band gap to a stack. However, a range of other better-integrated approaches are possible that offer similar efficiency to an infinite stack of such tandem cells[7]. The efficiencies of 38.8% have been achieved under 1 sun illumination using five junctions of III−V semiconductors[8]. In that aspect, III-V materials tandem on silicon represents to be a promising pathway to overcome the ~29% efficiency limit of a single c-Si solar cell.

Multijunction (MJ) solar cells with different bandgap absorb maximum solar spectrum and split it up to convert into energy that boost the output of the solar cell circumventing the Shockley-Queisser limit[6,8]. Monolithically grown MJ solar cells of III-V elements on lattice matched Ge or GaAs substrate increases the manufacturing cost due to the maximum conversion efficiency and low availability of these device. Si is an ideal alternative for Ge as lower substrate with suitable bandgap for 3junction (3J) solar cells. This is due to superior properties of Si being an excellent thermal conductor, high mechanical strength, nontoxic, low cost and abundant earth element[4]. MJ solar cells on Si bottom cell with a suitable bandgap have been implemented to establish Si based tandems. For two terminal (2T) MJ solar cell, bandgap should be carefully paired, for example: the top cell bandgap should be in 1.75-1.8 eV range of a dual

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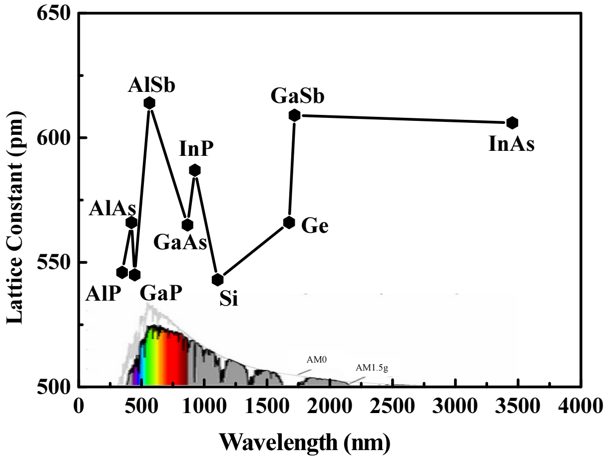


Fig. 1. III-V compound semiconductors for solar cell applications. Adapted from Ref. [35]

junction solar cell with Si bottom cell. Giving a good match GaInP has achieved 29.8% efficiency on a Si based dual junction solar cell and it has also gained 31.6% efficiency combining with GaAs on III-V solar cell. There are three approaches to grow III-V solar cell on Si substrates: (i) direct epitaxial growth and (ii) wafer bonding[9)], and (iii) mechanical stack bonding. However, lattice mismatch, high dislocation density and different thermal coefficient lead to the difficulties in the fabrication processes, cracking or bowing of the films in epitaxially grown III-V solar cell on Si substrate[9-11)]. As a result the epitaxially grown III-V/Si solar cell lacks in performance. To avoid these problems, III-V solar cells have grown on Si substrate with wafer bonding approach. Due to the different thermal expansion, difficulties were involved with the cracking thin film solar cells of Si and GaAs. This issue has been avoided by post-growth wafer bonding which has been demonstrated by Derendorf et al.[11)]. Continuous research is undergoing to fabricate economically feasible wafer bonding process for high performance III-V/Si tandem solar cells. Moreover, attaining ohmic interface for III-V semiconductor and Si bonding is difficult owing to high bonding temperature above 700°C which induce material defect and thermal strain in the III-V semiconductor on Si substrate. Tanabe et al.[12)] reported the ohmic interface formation through direct wafer bonding on III-V/Si based solar cell. However, the bonding process needs much time approx. three hours. A new approach has been stated with short processing time and low temperature which is known as "surface activated bonding" (SAB)[13)]. Fig. 1 shows the III-V semiconductor materials with respect to their lattice constants and bandgap energy that are suitable for solar cell applications.

Some recent progress in tandem devices were reported in solar cell efficiency tables (version 52) on a standardized basis for 1-sun multiple junction devices with high efficiency under the global AM1.5 spectrum (1000W/m^2) at 25°C[8)]. Spectrolab has fabricated 5J III-V MJ cell (bonded 2.17/1.68/140/1.06/ 073 eV) with high efficiency 38.8% and measured at National Renewable Energy Laboratory (NREL). Recently wafer bonded 3J GaInP/GaAs/Si tandem device fabricated by a joint effort of Fraunhofer Institute for Solar Energy (ISE) and the EV Group with 33.3% efficiency using 0.002 mm semiconductor layers of III-V compound semiconductors where the thickness of these layer is less than a twentieth the thickness of a human hair[14)]. One more new result of tandem device on 4-cm^2 monolithic, 2J, 2T GaAsP/Si was reported by a jointly Ohio State University (OSU), SolAero Technologies Corporation and the University of New South Wales, Sydney (UNSW) and evaluated at the US National Renewable Energy Laboratory (NREL)[15)].

In this study, the major factors that affect the growth of III-V tandem cells on Si substrate were studied with a brief overview of different growth mechanisms. This review work is arranged as follows: Theoretical approach for efficiency of III-V/Si solar cell and arial current matching are illustrated in section 2 and section 3 respectively. Sensitivity analysis in order to control the manufacturing cost is described in section 4. In section 5, different growth mechanisms such as silicon-hetero-epitaxy, wafer bonding, mechanical stacking are reported and finally in section 6 the issues of implementing the III-V/Si solar cell as well as a view of future development are stated.

2. Theoretical approach for efficiencies of III-V silicon solar cell

Determination of efficiency loss for distinct types of III-V/Si solar cells has been determined by an analytical mode, External Radiative Efficiency (ERE), ratio of radiatively recombined carriers against all recombined carriers which ascribed the resistance loss and non-radiative recombination loss. The external quantum efficiency (EQE) and open circuit voltage (V_{oc}) are the major factor to calculate ERE. A theoretical study by Lee et al.[16)] illustrated a mathematical formulation for determining the efficiency of III-V/Si solar cells. According their Superposition theorem the total current density J(V) of the solar cell is the sum of the record current density $J_{tot}(V)$ and short circuit current density J_{sc} given as:

$$J(V) = J_{sc} + J_{tot}(V) \tag{1}$$

$$J_{sc} = q\int_0^{\infty} \phi(E).EQE(E)dE \tag{2}$$

Where, $\phi(E) = \textit{incident photon spectrum}$ EQE can be expressed as

$$EQE(E) = \begin{cases} b, E \geq E_g \\ 0, E < E_g \end{cases} \tag{3}$$

Where, E_g= bandgap of material and b=EQE value.

The total recombination current $J_{tot}(V)$ connected to the radiative recombination current $J_{rad}(V)$, which as follows:

$$J(V) = \frac{J_{rad}(V)}{\eta_r} \tag{4}$$

Where, η_r= ERE which is individualistic of carrier injection.

Reflection and parasitic transmission losses of the top layer and the interfaces between junctions of the MJ solar cell have been neglected. Assuming all absorbed photons convert into electrical current, the following equation for the i-th junction has been demonstrated by

$$\phi_i(E) = \phi_{i-1}(E)(1 - EQE_{i-1}(E)) \tag{5}$$

Where, $\phi_{i-1}(E)\,\&\,EQE_{i-1}(E)$ represents incident photon. Lee et al.[16] also demonstrated that the I-V characteristics of MJ solar sell V_{tot} (J) which can be illustrated as follows:

$$V_{tot}(J) = \Sigma_{i=1}^{N} V_i(J) \tag{6}$$

Where, $V_i(J)$ is voltage of the i-th sub cell at current density J, $V_{tot}(J)$ is maximum power point (MPP) of efficiency considering the cell geometry as a constant. Due to the threading dislocation the minority carrier lifetime has been approximated as:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nr}} + \frac{\pi^3 N_d}{4} \tag{7}$$

Where, τ_{eff} is the effective minority carrier lifetime, τ_{rad} is the radiative lifetime, τ_{nr} non-radiative lifetime and N_d is the threading dislocation density. Due to the low carrier injection density, threading dislocation and the similar geometry factors,

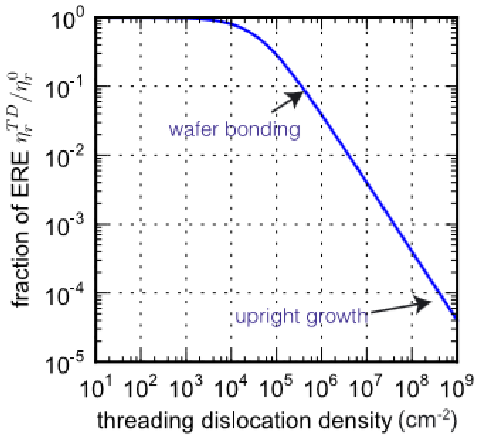


Fig. 2. Fraction ERE without dislocation η_r^{TD}/η_r^0 against threading dislocation densities. Reprinted from [16], with the permission from John Wiley and Sons

the ERE has been demonstrated as:

$$\frac{\eta_r^{TD}}{\eta_r^0} = \frac{\tau_{eff}^{TD}}{\tau_{eff}^0} \tag{8}$$

Considering thermal dislocation, ERE and effective minority carrier are represented as η_r^{TD} and τ_{eff}^{TD}. Whereas without thermal dislocation, ERE and effective minority carrier are noted as η_r^0 and τ_{eff}^0 respectively. The variation in ERE fraction and threading dislocation density for wafer bonded as well upright grown samples was presented in Fig. 2. This relation clearly shows the variation in the efficiencies of III-V/Si solar cells.

Theoretically, with different bandgap materials to attain higher efficiency solar cell, the number of sub cells need to be increased. It has been demonstrated that the theoretical efficiency of MJ solar cells achieve 86.8% with infinite number of junctions[17]. For a 4 junction solar cell, it can obtain efficiency above 55%[18]. In National Center for Photovoltaics (NCPV) the researcher demonstrated the highest potential efficiency of multijunction solar cell above 50%[19]. Fig. 3 demonstrated the efficiency obtained for the ERE of III-IV top cells. From the Fig. 3 it was observed that the highest efficiency of 41.9% was achieved for AlGaAs, Ga(As)PN and AlInGaP is by selecting 1.73 eV bandgap semiconductor as the top cell[16]. The efficiency variation for 3 junction III-V/Si solar cells against the top and middle cell bandgaps were also mentioned in Fig. 3. The EREs are presumed to be 100%. For InGaP/GaAsP, (Al)InGaP/InGa(As)P, (Al)InGaP/AlGaAs, Ga(As)PN and GaPN/GaAsPN/Si materials, the optical bandgap combination was 2.01 eV and

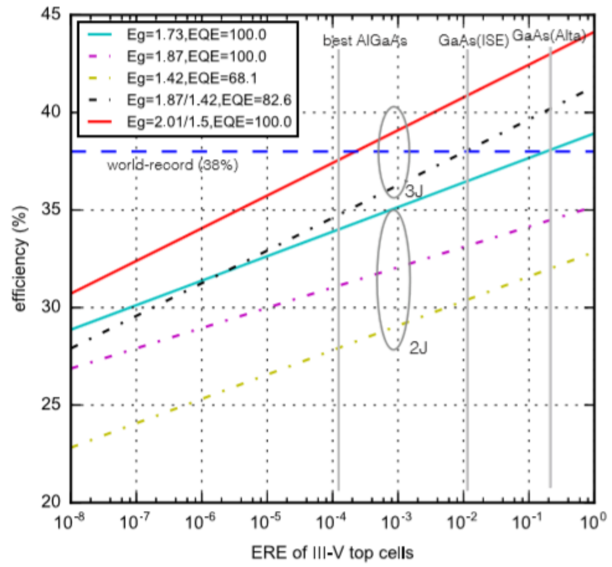


Fig. 3. One sun efficiencies ERE of various junctions. Reprinted from [16], with the permission from John Wiley and Sons

Table 1. Efficiencies at different EREs of Si tandem solar cells. Adapted from Ref. [4]

Junctions	External Radiative Efficiency (ERE)	Efficiency
2J	10^{-5}	32.5
	10^{-4}	34.0
	10^{-3}	35.2
	10^{-2}	36.5
	10^{-1}	38.0
3J	10^{-5}	35.9
	10^{-4}	37.5
	10^{-3}	39.2
	10^{-2}	40.8
	10^{-1}	42.5

1.50 eV. It was stated that Si based InGaP/GaAs has 36.3% efficiency where the optimal EQE is 82.6%[16].

It has been demonstrated that the optimal bandgap can be favourable within the 10^{-2}-10^{-4} [16]. It has been proved that the state-of-the-art III-V top cells reaches at 10^{-3} limits of ERE so it is believed that the III-V/Si solar cells could achieve 38% efficiency to upgrade the ERE by two order of magnitude[20]. With different efficiencies, the 2J and 3J silicon tandem silicon solar cells at different EREs are inventoried in Table 1.

3. Analysis of Arial Current Matching (ACM)

Current matching has been the fundamental step for the high efficiency MJ tandem solar cell. To meet the issue, either the thickness of the top sub cells is minimized or the area of Si

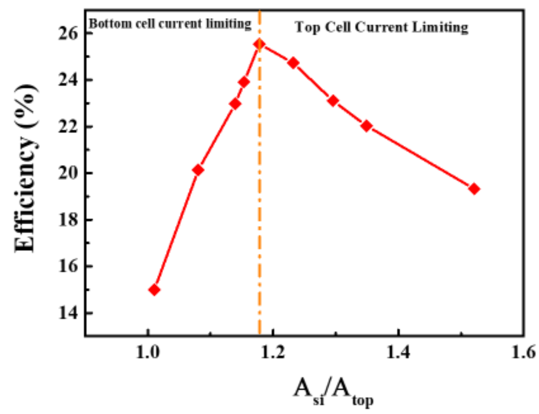


Fig. 4. Relationship between GaInP/InGaAs/Si 3J cell efficiency and the area ratio A_{Si}/A_{Top}. Adapted from Ref. [10]

bottom cell is enhanced. ACM technique was introduced to reduce the efficiency loss by current limitation. ACM permits the sunlight to disperse into the bottom Si cell improving the device efficiency by matching the current from bottom to the top cell. Due to the high sensitivity of the sub cell the thickness is difficult to control. However, current matching with area ratio can be computed in regard to the J_{sc} of the sub cell by below formula. J_1, J_2 and J_3 all are varying quantifiable current densities described from the part of Si bottom cell which is exposed to the full spectrum to the shadow formation due to top cell, respectively[10].

$$\frac{A_{Si}}{A_{top}} = (J_3 - J_2 + J_1)/J_1 \tag{9}$$

From the above formula it is clearly visible that $A_{si}>A_{Top}$ is needed for current matching if the bottom Si cell is the current limiting cell (i.e $J_2<J_3$). Fig. 4 clearly indicated the limiting condition for the current matching point of bottom and top cell to obtain maximum cell efficiency for GaInp/InGaAs/Si cell. It was observed that the optimized point was obtained for A_{Si}/A_{Top} nearing to 1.2.

4. Sensitivity Analysis

Efficiency under standard testing conditions (STC) is one of the important performance indicators. The good performance of a solar cell is not enough wherein the durability of the cells should be more than 20 years and cost deductive fabrication[9,12,21]. Single junction (SJ) Si solar cell implies a low fabrication cost and has a track record of long term outdoor operation[7,22]. Recently, the best 1-sun SJ solar cell has been

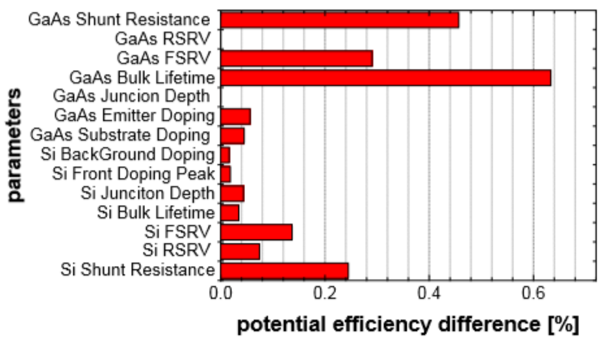


Fig. 5. Difference of potential efficiency with the variation in different fabrication parameters. Reprinted from [22], with the permission from Japan Society of Applied Physics

shown a STC efficiency 26.3% while the practical efficiency limit was calculated at 29.4%[15,16]. Dimroth et al.[9] has demonstrated a 46% efficiency of concentrator solar cells made from III-V semiconductors. The efficiency of a tandem solar cell is influence by material and structural parameters. There are various parameters including shunt resistance, background doping (bulk doping), front doping (emitter doping) peak, junction depth, bulk lifetime, front surface recombination velocity (FSRV) and rear surface recombination velocity (RSRV) for both the top and bottom cell effect the efficiency of the cell. In order to achieve better efficiency of the top cell the shunt resistance, bulk lifetime and the junction depth of the top cell were increased whereas the background doping (bulk doping), front doping (emitter doping) FSRV and RSRV were decreased and for the bottom cell, FSRV and RSRV were decreased whereas the other parameters were increased to obtain the high efficiency. It was observed that FSRV, shunt resistance, and the bulk lifetime of the top cell have the potential to increase the efficiency[14]. By improving the shunt resistance and the bulk lifetime of the top cell an additional potential efficiency gain of ~0.46% (absolute) and ~0.63% (absolute), respectively can be achieved as shown in Fig. 5. By minimizing the FSRV, the potential efficiency could be ~0.29% (absolute). Optimizing the shunt resistance of the bottom cell could potentially increase the tandem cell efficiency by ~0.25 (absolute). A potential efficiency gain of ~0.14% (absolute) can be achieved by optimizing FSRV. Implementing the highest potential efficiency gain from all the examined parameters, the efficiency of the tandem cell was still below 35.8% as predicted in the literature of Ren et al.[23]. Due to lack of considerable simulation, optical losses such as the coupling between the top cell and bottom cell, electrical losses like contact resistance, the efficiency is still below that limit value.

According to simulation results, all the low sensitive parameters have very low impact on the efficiency variation. These factors need not to be controlled during the manufacturing process to cut down the fabrication cost of the tandem solar cells.

5. Growth mechanisms

As shown in this Fig. 3, III-V materials which are lattice matched to silicon is very inadequate. The difficulties comes from the III-V materials which are lattice mismatched. Having same lattice constant monolithically epitaxial grown III-V multi junction cells requires epitaxial layers to provide high crystallinity which is important to achieve high efficiency. Difficulties were connected with thermal expansion coefficients between III-V semiconductors and silicon. In the epitaxial process the substrate is heated to the high growth temperature 600-700°C and then cool down to room temperature which may leading cracking, bowing or bending in the III-V on silicon wafers. The thermal expansion coefficients of silicon is $2.6\times10^{-6}\,K^{-1}$ wherein thermal expansion coefficients of III-V semiconductors lies between 4.7×10^{-6} to $5.7\times10^{-6}\,K^{-1}$ [12]. III-V/Si solar cell results are mainly attained by silicon-hetero-epitaxy, wafer bonding, mechanical stacking.

5.1 Direct hetero-epitaxy of III-V semiconductor on silicon

III-V/Si solar has been successfully grown by Umeno et al.[24] and Yang et al.[25] with a maximum efficiency 20% for AlGaAs/Si solar cells under AM0 has been demonstrated by them in 1990s. Direct growth III-V semiconductor has advantage of using only one substrate and one epitaxial process with cheap manufacturing cost. However, fabrication of solar cell using epitaxial technique is quite challenging. It has been proved that III-V semiconductors can be directly grown on silicon substrates without buffer layers in spite of the lattice mismatch between III-V and silicon (Fig. 6 (a)). It has been demonstrated GaAs solar cell grown on silicon substrate with 18.3% efficiency at AM0 and 20% at AM1.5[26,27].

5.2 Hetero-epitaxy growth with buffer layer

Nowadays, most of the attention was revolved to using graded buffer layers to transfer the lattice constants of silicon to that of III-V materials. Materials with the similar or closely

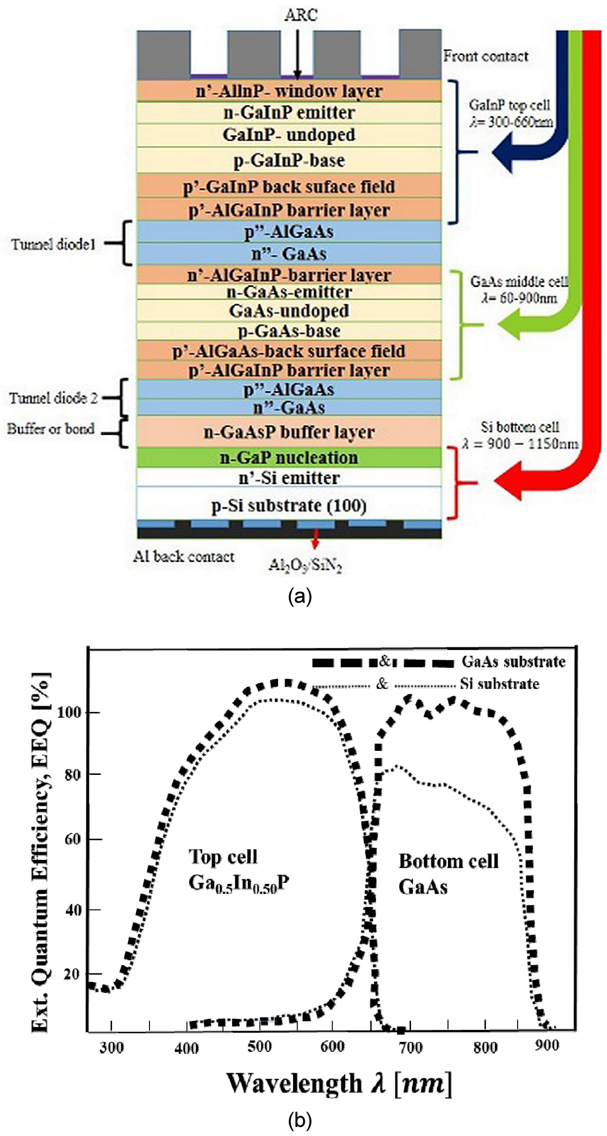


Fig. 6. (a) Schematic diagram of GaInP/GaAs//Si triple junction direct growth solar cell. Adapted from Ref [35] (b) EQE of a GaInP/GaAs tandem solar cell grown on Si compared with an identical reference structure on GaAs. Adapted from Ref. [9]

similar lattice constant to silicon are initially grown on silicon substrates which composition is moderately changed to match the lattice constant of the III−V materials. The two of the most successful graded buffer layers are Si_xGe_{1-x} and $GaAs_yP_{1-y}$[26).

5.2.1 Graded Si_xGe_{1-x} buffer

On the germanium substrate, the epitaxial growth of III-V multi junction solar cell is accepted which has been examined by the research group in Massachusetts Institute of Technology (MIT) to decrease the threading dislocation density to ~10^6 cm^{-2} using chemical mechanical polishing half way between the growth of SiGe. Efficiency 18.1% 1J of GaAs solar cell has been demonstrated by Andre et al.[28). Before extending to the bottom silicon SiGe absorb the maximum photons with low band gap and thick layers (typically 10 μm) which make the bottom silicon as an inoperative substrate.

5.2.2 Graded $GaAs_yP_{1-y}$ buffer

It is difficult to direct grow III-V solar cell on Si substrate consisting one substrate and one epitaxial process which reduces the manufacturing costs. For the direct heteroepitaxy Gallium phosphide (GaP) is the most evident choice of III-V material. Fig. 1 shows the close matching of lattice parameter against silicon. GaP has low absorption due to its indirect bandgap energy of 2.26 eV and it has low lattice-mismatch to Si. Normally for a 2J device the top cell is GaAsP (1.7 eV) and for 3J device is GaInP (2.01 eV)/GaAsP (1.5 eV)[12). To avoid any potential cross contamination it is needed to separate the growth of an n-GaP nucleation layer on Si from the growth of $GaAs_{1-y}P_y$ metamorphic buffer and GaInP/GaAs tandem solar cell structure. In the future it has to be examined how these process can be combined by avoiding any material related defects on Si. The researchers have implemented GaInP/GaAs solar cell structures (near about 790 nm thick $Ga_{0.5}In_{0.5}P$ and 1.9 μm GaAs absorber) on the GaAsP/Si templates.

The thickness of buffer layer $GaAs_yP_{1-y}$ was 180nm. The same process has been applied to grow a reference tandem cell on GaAs substrate. Fig. 6(b) denotes the quantum efficiencies of both devices. It is clearly visible the same performance of GaInP on GaAs and Si substrate whereas GaAs bottom cell faces difficulties from the low diffusion length of minority carriers. There are fundamentally two probable explanations for this result: either the top GaInP cell is less sensitive to dislocations or the further growth of GaAs and tunnel diodes on buffer layer GaAsP leads to a depletion of the threading dislocation density. GaAs bottom cell has low quantum efficiency on Si therefore the overall current of the tandem cell is restricted under AM1.5G[6).

Lee et al.[16) demonstrated a 15.3% efficiency $GaAs_{0.76}P_{0.24}$ single junction solar cell on a GaP/Si template. Dimroth et al.[9) demonstrated a 16.4% efficiency (AM1.5G) for the best directly grown GaInP/GaAs tandem solar cell on Si, against the 27.1% for reference structure on GaAs. The efficiency loss comes from the high threading dislocation density (>10^8 cm^{-2}) so that the further optimization of the buffer layer $GaAs_yP_{1-y}$ needs to improve the threading dislocation density and the overall performance of the tandem solar cells on Si.

5.3 Wafer Bonding

Fraunhofer ISE demonstrated wafer bonded triple junction GaInP/GaAs/Si solar cells[22,24]. The process was kept optimized. Osaka City University examined one-sun-efficiency of 25.5% for GaInP/GaAs/Si 3J solar cell[25]. Recently, using the surface activated bonding technique the two terminal 3J GaInP/GaAs/Si cell with 33.3% efficiency has been demonstrated by Fraunhofer ISE, which is shown by Fig. 7. In optoelectronic industry direct wafer bonding is an accepted technique because it creates covalent bonds between the different materials. III-V solar cells are grown lattice matched on a GaAs or Ge substrate without causing much dislocation defects. These are connected at moderate temperature. The wafer bonding layers are very thin. This is the reason parasitic resistance and optical loss are much smaller than the buffer layer used in hetero-epitaxy. Surface morphology is one of the difficulties of direct wafer bonding[21,26). Particles and local areas creates voids at the wafer bonded interface. This is due to high surface roughness, work function mismatch and carrier transport across the interface that strongly alter the electron affinity, doping levels and the electrically active defects level of the cell. These kind of defects may trap free carriers. During the surface activation prior bonding, these interfacial defects may be occurred due to unsaturated bindings, impurities or defects[21,27,28]. So surface roughness should be less than 0.5 nm[29]. A low interface resistance is an important physical property of the semiconductor bond because concentrator solar cells have high current densities. The electrical conductivity of direct wafer bonds between Si and III-V semiconductors was examined and optimized to gain interface resistance below 4 m $\Omega.cm^2$ [30]. At first the III-V layer is grown on a III-V substrate. By removing III-V substrate, the epitaxial wafer is bonded onto Si. III-V solar cell has the capacity to reuse the III-V wafer as many times as possible making the procedure economically feasible. In general, there is three steps: (i) wafer processing, (ii) pre bonding the wafers by mechanical compression, (iii) post annealing the wafers to form strong bonds. The most successful approach is two of the wafer pre-processing to fabricate high performance multi junction solar cells[26].

At first wet chemical etching is used to hydrogen terminated surface to bring wafer via hydrogen bonds. After that post anneal desorbed the hydrogen and creates covalent bond in the interface. In the second step, plasma or fast argon atom uses to activate the surface of each wafer which is known as surface activated bonding (SAB). The bonds between the wafers could be strong by the post annealing process which can damage the wafer due to the difference of thermal expansion.

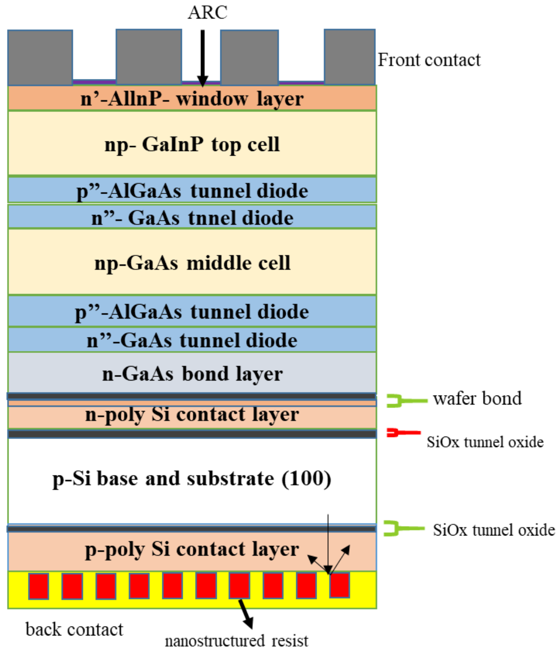


Fig. 7. Schematic diagram of GaInP/GaAs//Si triple junction wafer bonded solar cell. Adapted from Ref. [35]

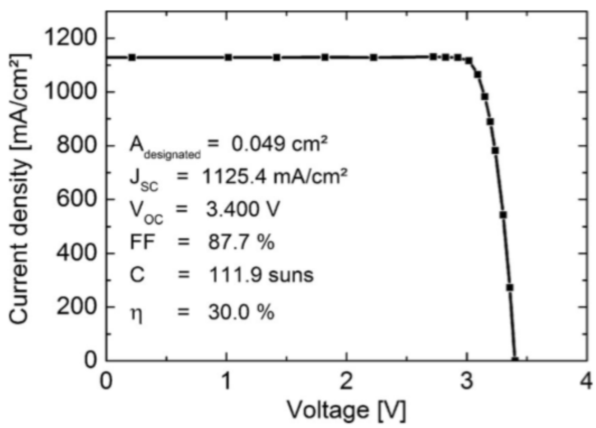
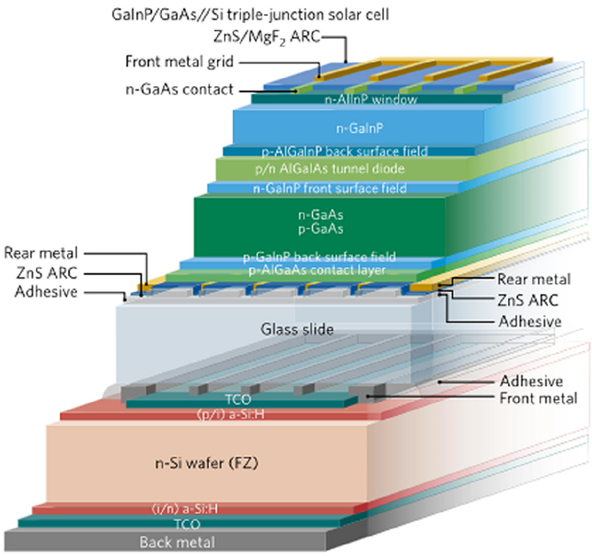
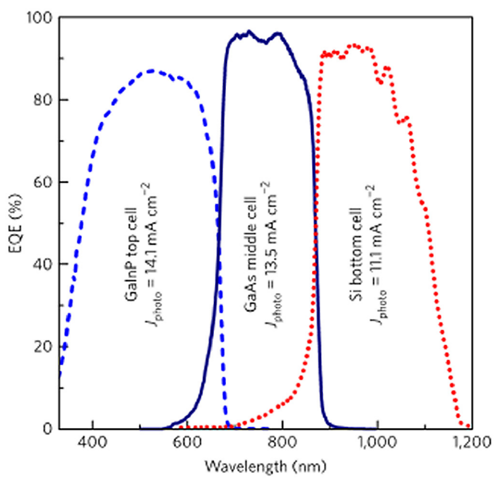


Fig. 8. I-V curve with mask where the efficiency achieves highest value of 30.0% GaInP/GaAs//Si 3J solar cells (from Ref. [29])

High efficiency four or five junction solar cells are used in these approaches to the fabrication. Most of the III-V/Si multijunction solar cells do not need post annealing steps so they were implemented by SAB. Efficiency of wafer bonded GaInP/GaAs//Si 3J solar cells has been demonstrated from the I-V curve measured with mask where the efficiency achieves highest value 30.0% at 112 suns for higher concentration factors[29] which is shown in Fig 8. It is stated that it was the first demonstration of a MJ solar cell two terminal with Si bottom cell with such a great efficiency.



(a)



(b)

Fig. 9. (a) Schematic diagram of GaInP/GaAs//Si triple junction mechanical bonded solar cell; (b) Transfer matrix optical modelling of absorption in the GaInP/GaAs//Si active solar cell layer with 3 middle cell. Reprinted from [34], with the permission from Springer Nature

5.4 Mechanical Stack

Direct epitaxial growth of III-V/Si MJ solar cells can be fabricated by mechanical stacking. Mechanical stack prevents the lattice dislocation whereas it need a metallic grid or intermediate layer at the interface to form the stack. This metallic grids adds up the disadvantage by causing optical loss. This loss can be avoided by wafer bonding.

In 1989, L Fraas et al.[30] developed the first mechanical GaAs/GaSb concentrator cells with efficiency up to 32.6% at 25°C at 100 suns. Takamoto et al.[31] reported an upgraded version of four terminal III-V solar cell that had a combined efficiency of 28.16%, verified by AIST. A series of papers jointly with National Renewable Energy Laboratory (NREL), Ècole polytechnque federale de Lausanne (EPFL), Swiss Center for Electronics and Microtechnology (CSEM)[8,32,33] reported of mechanically stacked III-V/Si solar cell with efficiency of a 32.8% 2J GaAs/Si and 35.9% 3J GaAs/Si, respectively[35,36]. The Sharp reported to achieve a 33.0% efficiency of GaInP/GaAs/Si 3J solar cells which was shown in Fig. 9[34,35]. A research group at McMaster University demonstrated a 25.5% efficiency GaInP/GaAs/Si 3J solar cell with the mechanical stack using direct metal interconnect[32].

6. CONCLUSION

In this review work, the recent progress of III-V tandem solar cells and their brief overview of growth mechanisms were discussed in detail. III-V materials have the potential to overcome the Shockley-Queisser limit. However, there are many hurdles to grow the MJ III-V materials on Si substrate as Si with other materials often demands similar qualities which was resolved using graded buffer layers to transfer the lattice constants of silicon to that of III−V materials. Though the optimization was needed for the graded $GaAs_yP_{1-y}$ buffer to reduce dislocations and improve the device performance. Besides that, the lattice mismatch problem was solved through the wafer bonding approach. In spite of different fabrication procedures made to develop III-V tandem solar cell, the research result by various research groups were reported here. Significant parameters like shunt resistance, background doping (bulk doping), front doping (emitter doping) peak, junction depth, bulk lifetime, FSRV and RSRV play a vital role to affect the efficiency which were thoroughly reviewed. Theoretical approaches to design efficient tandem cell with an analysis of state-of-art silicon solar cells was discussed in this work. Several reports confirmed that the V_{oc} is an important key to increase the efficiency. At present, GaInP/GaAs/Si silicon tandem solar cell grown by mechanical stacking and direct wafer bonding can achieve more than 30% efficiency. A highest cell efficiency reported for wafer bonded GaInP/GaAs/Si tandem solar cell is 33.3% with a V_{oc} = 3.984 V and mechanical stack bonded GaInP/GaAs/Si is 35.9% with a V_{oc} = 2.52 V[5]. But the mechanisms are really cost effective. So cost deductive wafer reuse technology needs to be invented. A proper realization of new design with appropriate charge transport, huge band gap materials, and good contact layer with low defect state is required. Implementing an active Si junction as a third bottom sub cell, the conception of III-V/Si solar cell can be expanded. Although the crystalline Si solar cell efficiency is far better than III-V tandem solar cell, the III-V tandem solar cell showed a promising result which will open a new door to improve the applications. Even the outcome is lower than as awaited, the future studies on III-V tandem solar cell will attain highest efficiency with incorporating more junctions.

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