Current Photovoltaic Research 7(3) 76-84 (2019)
DOI:https://doi.org/10.21218/CPR.2019.7.3.076

pISSN 2288-3274
eISSN 2508-125X

Potential Wide-gap Materials as a Top Cell for Multi-junction c-Si Based Solar Cells: A Short Review

Duy Phong Pham[1)] · Sunhwa Lee[1)] · Sehyeon Kim[1)] · Donghyun Oh[1)] · Muhammad Quddamah Khokhar[1)] · Sangho Kim[2)] · Jinjoo Park[3)] · Youngkuk Kim[1)] · Eun-Chel Cho[1)] · Young-Hyun Cho[1)] · Junsin Yi[1)]*

[1)]College of Information and Communication Engineering, Sungkyunkwan University, Gyeong-do 16419, South Korea
[2)]Department of Energy Science, Sungkyunkwan University, Natural Science Campus, Gyeong-do 16419, South Korea
[3)]Major of Energy and Applied Chemistry, Division of Energy & Optical Technology Convergence, Cheongju University, Chungbuk 28503, South Korea

Received June 26, 2019; Revised September 3, 2019; Accepted September 4, 2019

ABSTRACT: Silicon heterojunction solar cells (SHJ) have dominated the photovoltaic market up till now but their conversion performance is practically limited to around 26% compared with the theoretical efficiency limit of 29.4%. A silicon based multi-junction devices are expected to overcome this limitation. In this report, we briefly review the state-of-art characteristic of wide-gap materials which has played a role as top sub-cells in silicon based multi-junction solar cells. In addition, we indicate significantly practical challenges and key issues of these multi-junction combination. Finally, we focus to some characteristics of III-V/c-Si tandem configuration which are reaching highly record performance in multi-junction silicon solar cells.

Key words: III-V/Si solar cells, Multi-junction silicon solar cells, High efficiency solar cells

Nomenclature

J_{sc} : short-circuit current density, (mA/cm^2)
V_{oc} : opec-circuit voltage (V)
FF : fill factor, (%)
Eff : Efficiency, (%)
SHJ : Silicon heterojunction solar cells
PV : photovoltaic
MJSSC : multi-junction silicon solar cells
TSSC : tandem silicon solar cells
SE : spectral efficiency, (%)
EQE : external quantum efficiency, (%)

1. Introduction

Monocrystalline silicon (c-Si) based solar cell modules have played an important role in the photovoltaic (PV) market for decades which has gained around 60% of the PV market. The cost per watt of PV modules has gradually decreased in recent years for an economic competitiveness. To obtain the effective competition about commercial cost, the conversion performance of silicon solar cells has been steadily increasing while other efforts have been focusing on improve installation, cabling or inverters. Practically, an improved cell performance is still crucial solution for overall low-cost of PV system. Presently, the cell efficiency-improvement has been focused mainly on the optimization of shadow losses and parasitic recombination losses due to the front metallization and stacks of the front contact layers[1,2)]. In addition, the reduction of surface-recombination loss as well as losses due to metal/semiconductor contact have been attended[3,4)]. Consequently, the world record cell efficiency reaching over 25% and even 26.7% have been achieved recently by various research groups[5-9)]. Table 1 summarizes some currently high record efficiency of various institutes and companies. It shows that a confirmed record performance of 26.7% was recorded recently in 2017 by Kaneka Solar Energy company[5)]. Although reaching over 26% cell performance in the laboratory-level devices which nearly reaching the limited-threshold of theoretical efficiency for single-junction silicon cell of 29.4%, the state-of-the-art manufacturing PV of c-Si solar cells has practically gained the stable conversion efficiencies only around 20% - 21% for a long time[10)]. These imply that the high efficiency development for

---

*Corresponding author: junsin@skku.edu

Table 1. Summary of the record confirmed single-junction silicon solar cell efficiencies

Single−junction structure	Cell efficiency (%)	Cell area (cm^2)	Year	Group/Institude
HBC	**26.7**	79	2017	Kaneka[5]
TOPCon	**25.7**	4	2017	Fraunhofer[6]
HIT rear junction	**25.6**	143.7	2014	Panasonic[7]
IBC	**25.2**	153.49	2012	SunPower[8]
p-type POLO-IBC	**26.1**	3.9857	2018	ISFH[9]
p-type PERC	**25.0**	4	1998	UNSW[9]

Table 2. Highest single-junction performance of wide-gap materials as top cell in silicon tandem solar cells

Top cell material	Band Gap (eV)	Cell efficiency (%)	Cell area (cm^2)	Group/Institude
III-V GaAs (thin film)	1.5	**28.8**	0.99	Alta devices[16]
GaInP	1.82	**21.4**	0.25	LG electronics[17]
II-VI CdTe	1.5	**22.1**	0.47	First solar[9]
CZTS	1.8	**11.0**	0.23	UNSW[9]
Perovskite	1.6	**22.7**	0.09	KRICT[18]
Si (amorphous thin film)	1.7	**10.2**	1.0	AIST[9]
CIGS (thin film)		**22.9**	1.0	Solar frontier[9]

mono-junction silicon solar cells are substantially limited. Consequently, numerous efforts have focused on a multi-junction design which stacks several solar cells in series[10-13]. In such design, the thermalization losses is to significant reduction due to considerable absorption in short wavelength of wide-gap top sub-cell and the other ranges of the solar spectrum are absorbed by medium and narrow-gap of middle and bottom sub-cells, respectively. A world record performance of 38.8% was gained by Spectrolab with multi-junction III-V semiconductor design[14]. In other aspect, c-Si based multi-junction configurations are intensive potential to gain a module-performance over 30%[11,15]. The advantage of Si-based multi-junction solar cells is to possibly significant commercial cost-reduction compared with III-V materials. A key challenge of such multi-junction solar cells is to choose appropriate materials as a subcell for superior cell efficiency while still maintain effective low-cost.

Consequently, we briefly review the state-of-art characteristic of wide-gap materials as sub-cell in c-Si based multi-junction solar cells. In addition, we aim to provide the path for choosing top-cell partners for the silicon tandem solar cells. Finally, we summarize some characteristics of III-V/Si tandem solar cells which are reaching highly record performance in multi-junction silicon solar cells (MJSSC).

2. The state−of−art characteristic of wide−gap materials

Table 2 summaries highest single-junction efficiencies of materials which has played a role as top sub-cell in MJSSC[9,16-18]. In these materials, hydrogenated amorphous silicon (a-Si) has been used as top cell in tandem silicon solar cells (TSSC) for decades. The confirmed efficiency of 14.8% has been recorded for thin film silicon based double-junction solar cell; so called "miromorph" tandem solar cells, with an a-Si:H/microcrystalline silicon (μc-Si:H) tandem structure[19] as shown in Fig. 1. This structure normally suffers from low current density (J_{sc}) of a-Si:H top cell and low open-circuit voltage (V_{oc}) of nc-Si:H bottom cells. Recently, some reports implemented the crystalline silicon (c-Si)-based tandem solar cells with a-Si or hydrogenated amorphous silicon germanium (a-SiGe) as top cells. For example, J. Fang *et al.*[20] showed 14.26% of a-Si/HIT double-junction structure with wide-gap a-Si:H front sub-cell and a SHJ bottom cell. This structure gained a high overall V_{oc} of 1.561 V and a significantly high J_{sc} of over 14 mA/cm^2 [20]. In addition, our group carried out two-terminal TSSC with a-SiGe:H top sub-cell and silicon heterojunction (SHJ) bottom cell (a-SiGe:H/SHJ tandem), as shown in Fig. 2[21]. A high efficiency of 16.04% was recorded with high V_{oc} of 1.5 V and J_{sc} of 15.19 mA/cm^2 as shown in Fig. 3. The advantage of a-SiGe:H top cell is to a higher absorption coefficient in the long

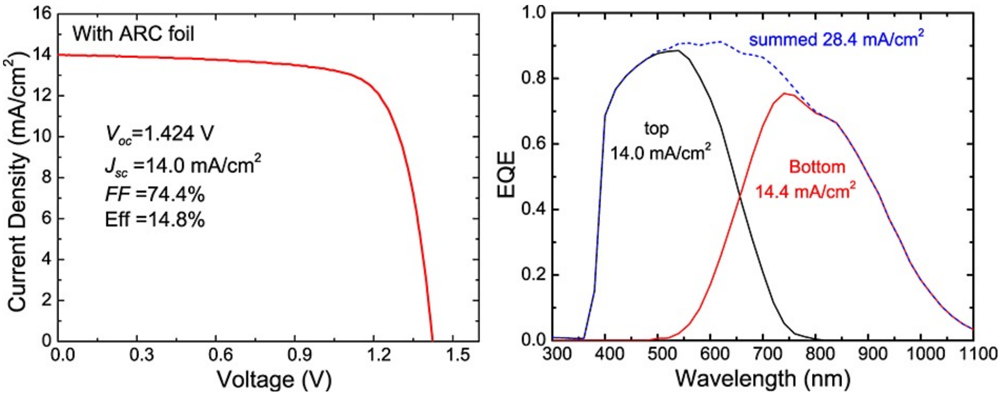

Fig. 1. J-V and EQE curves of a "micromorph" tandem solar cell with the highly confirmed efficiency. Reprinted from (19), with the permission from John Wiley and Sons

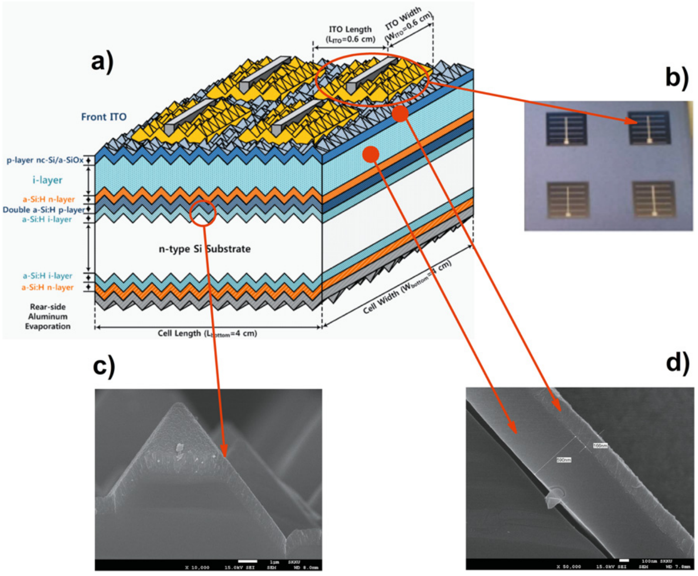

Fig. 2. a) TSSC configuration with a-SiGe:H top cell and SHJ bottom cell; b) Front-side view of TSSCs with screen-printed Ag-gird electrodes; c) Cross-section SEM image of the textured wafer surface; and d) Cross-section SEM image of a TSSC. This figure was reprinted from (21)

wavelength range compared with a-Si:H and thus higher J_{sc}. However, it can be seen that the obtained device performance is still significantly lower than 26.7% of single silicon bottom cells, as shown in Table 1. In addition, in general, the disadvantage of a-Si as well as a-SiGe:H is the light-induced degradation and in addition suffers from low-current density. Consequently, for gaining highest performance of MJSSCs, the selection of top cell partners has been a considerable challenge. Many efforts have focused to give convincing argument. How to appropriately select a top cell partner for MJSSCs and what maximum efficiency can these such tandem can reach are still a large debate.

Z. Yu *et al*. suggested that top cell partners for such MJSSCs should be selected based on spectral efficiency (SE) which is a little-known concept[22]. It defined as:

$$\eta(\lambda) = V_{oc}.\ FF.\ J_{sc}(\lambda) / I\ (\lambda),$$

in which η (λ) is spectral efficiency, I (λ) is the spectral irradiance (W m^{-2} nm^{-1}) and J_{sc} (λ) is the short-circuit current density per unit wavelength (A m^{-2} nm^{-1}) as denoted as following:

$$J_{sc}\ (\lambda) = q.\ \lambda\ EQE\ (\lambda).\ I\ (\lambda) / (h.c),$$

with q and h are elementary charge and Planck's constant, respectively; EQE (λ) is the external quantum efficiency and c is the speed of light in vacuum[22].

From above definitions, it indicates that spectral efficiency is understood as efficiency at each wavelength and it seems to analogous with EQE and J_{sc}. It is completely possible to

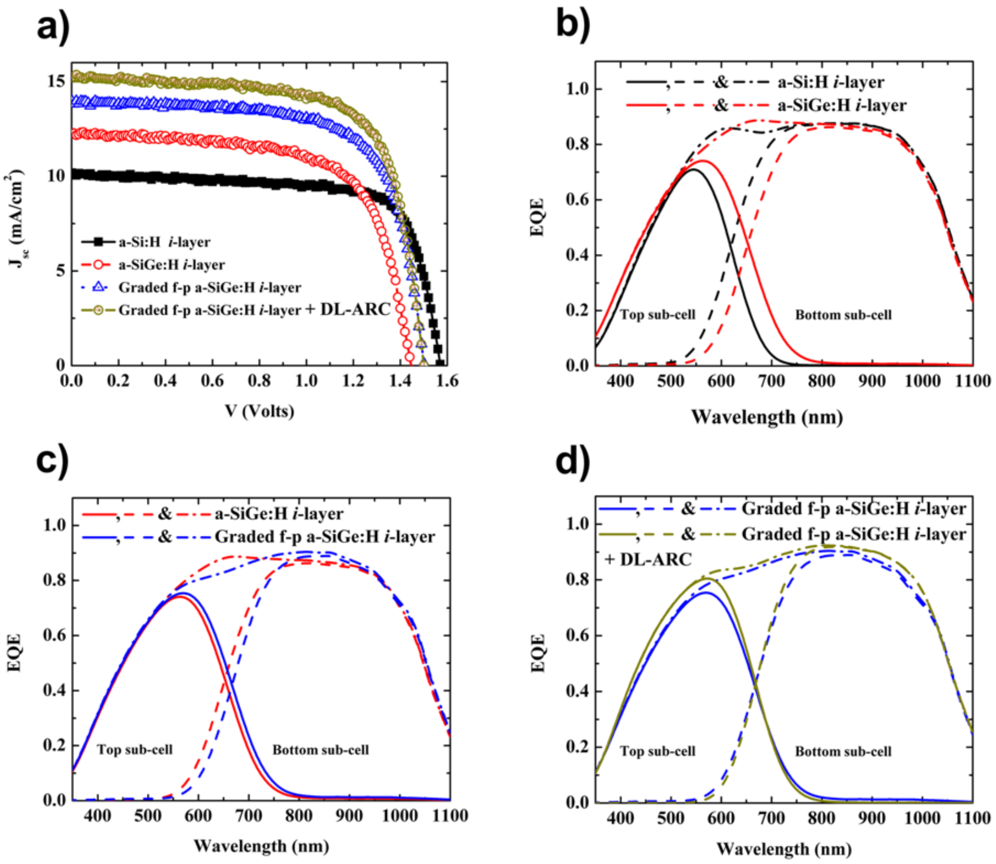

Fig. 3. J-V and EQE curves of TSSCs with a-Si:H and a-SiGe:H top sub-cells. This figure was reprinted from (21)

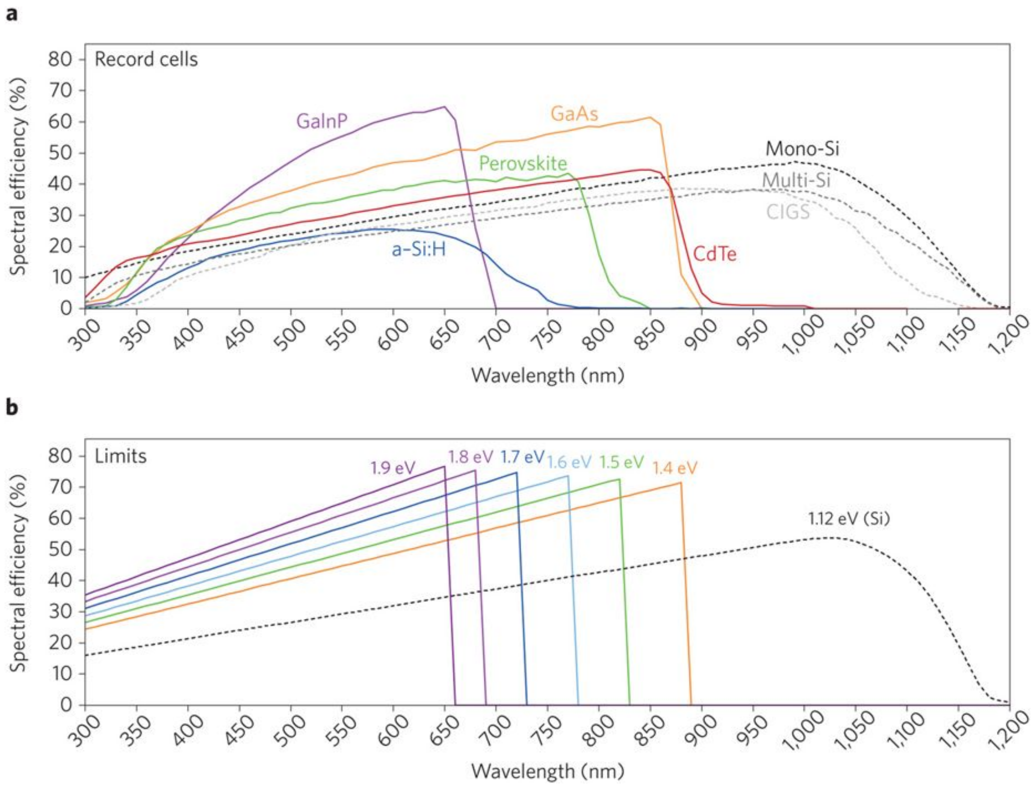

Fig. 4. a) Spectral efficiencies (SE) of some record single-junction cells which are potential as top (solid line) or bottom (dashed line) cells; and b) Limiting SE of ideal top cells. Reprinted from (22) with the permission from Springer Nature

Table 3. Maximum possible efficiencies of silicon-based tandem PV cells pairing existing record top and bottom cells. This table is adapted from (22), with the permission from Springer Nature

Top cell	AM1.5G efficiency (%)	Band Gap (eV)	Fraction of detailed balance efficiency (%)	Tandem efficiency with record mono-Si cell* (%)	Tandem efficiency with record multi-Si cell* (%)
GaInP	20.8	1.81	77	34.5 (35.1)	32.1 (32.6)
GaAs	28.8	1.42	87	34.9 (35.5)	33.6 (34.2)
CdTe	21.5	1.45	66	27.3 (27.7)	26.0 (26.4)
Perovskite	20.1	1.47	62	29.2 (30.2)	27.4 (28.4)
Perovskite	17.1	1.75	61	29.0 (29.7)	26.8 (27.5)

*The efficiencies in parentheses correspond to mechanical stacking; those not in parentheses correspond to coupling with a beam splitter. The V_{oc} of the silicon cell was adjusted to account for filtered illumination.

determine spectral efficiency based on J-V curve features and EQE spectrum data.

Z. Yu *et al.* also depicted the SE of some standard record cells as shown in Fig. 4[22]. The results indicated clearly that although a-Si:H material possess an ideal wide band-gap for a top sub-cell in TSSC, its SE, i. e. efficiency converts each wavelength to electricity, was poorer efficiency than the others and even than the mono-crystalline silicon cell in the short wavelength[22]. As a results, their tandem structure will lead to less performance than the bottom cell alone[22]. The authors discussed that GaInP which owns a similar band-gap to a-Si:H, seems to an appropriate selection for top cell due to effective SE in short wavelength (lower 650 nm)[22]. Thomas P. White *et al.* proposed the requirements for top cell in TSSCs[15]. These authors indicated that the efficiency of top-cell should at least range from 14% (for 2 eV of band-gap) to 22% (for 1.5 eV of band-gap) to gain 30% TSSC performance[15]. Some other requirements for top cell such as band-gap, diffusion length, luminescence efficiency, and absorption coefficient which can effect directly on MJSSCs was conducted systematically[15]. Especially, they demonstrated that an efficiency over 30% of MJSSCs can obtain with some special requirements for top-cell thin-film materials such as the luminescence efficiency in range of 10^{-5} and the carrier diffusion lengths on the order of 100 nm[15]. Experimentally, a high efficiency of over 30% has achieved by many research groups with III-V/c-Si MJSSCs[11,12,22]. Table 3 summaries some recent results for MJSSCs[22]. It indicates that the highest performance is presently achieved with III-V/c-Si multi-junction designs. In next section, important characteristics of III-V/c-Si multi-junction solar cells (III-V/Si MJSC) will be addressed in detail.

3. Characteristic of high efficiency multi-junction III-V/Si solar cells

The combination between high quality III-V material with c-Si has been an attractive strategy for photovoltaic device in recent years[23-25]. The approach for developing III-V cells on top of wafer Si substrates has been addressed in recent years. Presently, III-V multi-junction cell configurations have reached to the highest sunlight-electricity conversion of 38.8% for a five-junction solar cells under 1-sun illumination[26] and 46% for a four-junction under concentrated illumination[27]. However, these kinds of cells are normally prepared on expensive substrates such as Ge, crystalline -GaAs, or InP, and thus leading to high-commercial price. As a results, using wafer silicon as an alternative substrate for high and low-cost multi-junction devices appear on the roadmap of many research groups and companies. Strategies to apply III-V on silicon substrate; for example, growing epitaxy III-V layers directly on silicon wafer for two-terminal MJSSCs[28], have been proposed in recent years[29]. However, the different lattice constant as well as thermal expansion coefficient, high defect densities of III-V materials, and degradation during the epitaxy period of the c-Si bottom cell remain significant challenges which limit the efficiency of the two-terminal III-V/Si MJSCs. One of solutions for this issue is to fabricate separately top and bottom sub-cells and then stack them together at low temperature by various mechanisms popularly known as wafer bonding[30] or mechanical staking[31]. As summarized in Table 4, the four-terminal III-V/Si MJSCs gained higher efficiency than two-terminal ones. In four-terminal cell design, a stable wafer-bonding mechanism requires a tunnel junction, polished wafer surfaces with average roughness (RMS) below 1 nm[32], and clean room environment while the mechanical staking eliminates these

Table 4. Record tandem efficiency achieved for a range of top-cell materials and coupling configurations. This table is adapted from Ref. (22) with the permission from Springer Nature

Top cell material	Bandgap (eV)	Efficiency (%)	Year	Group/institute	Coupling
III-V					
AlGaAs	1.6	**25.2**	2012	Univ. Tokyo	Two-terminal; fusion bonding
AlGaAs	1.6	**21.2**	1998	Nagoya Inst. Tech.	Two-terminal; epitaxial growth
GaInP	1.8	**29.8**	2016	NREL	Four-terminal; mechanical stack
II-VI					
CdZnTe	1.8	**16.8**	2010	EPIR Tech	Two-terminal; epitaxial growth
Perovskite					
$CH_3NH_3PbI_3$	1.6	**19.2**	2016	EPFL	Two-terminal; direct deposition
$CH_3NH_3PbI_3$	1.6	**22.8**	2015	EPFL	Four-terminal; mechanical stack
$CH_3NH_3PbI_3$	1.6	**28.0**	2015	Kaneka	Four-terminal; optical coupling
$CH_3NH_3PbBr_3$	2.3	**23.4**	2015	UNSW	Four-terminal; optical coupling

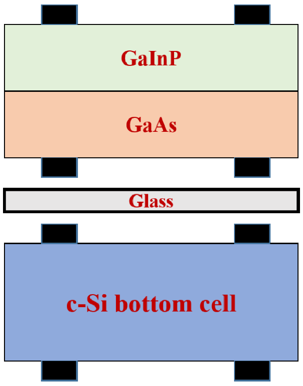

Fig. 5. Schematic diagram of III-V/c-Si MJSSC with GaInP/Ga top sub-cell and c-Si bottom cell

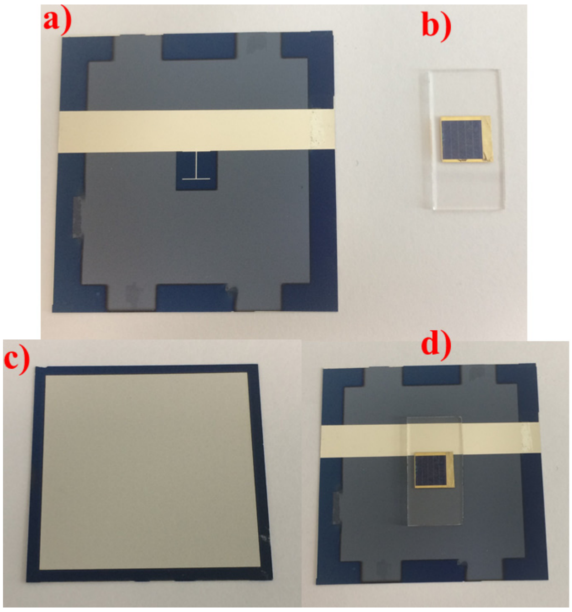

Fig. 6. Experiment III-V/c-Si MJSSC with a) front-side SHJ bottom cell design, b) front-side III-V cell epoxy-bonded on glass, c) back-side SHJ bottom cell, and d) III-V/c-Si MJSSC design

requirements and thus offers a lower-cost solution[11)].

Here, our group have implemented a mechanically stacked III-V/Si four-terminal MJSSC including of a GaInP/GaAs tandem top cell and SHJ bottom cells. A drawback of SHJ solar cells is attributed to parasitic light absorption, especially in short wavelength, at the stack front contact layers such as passivation a-Si:H and TCO films. The combination of a SHJ with wide gap top cell as a GaInP top cell can minimize this loss because the wide-gap top cell can effectively converse the short-wavelength radiations up to 690 nm and the longer-wavelength radiations can be achieved in SHJ bottom cell. Fig. 5 shows a schematic diagram of our III-V/Si tandem design. In addition, Fig. 6 shows the experiment photos of the four-terminal multi-junction cell configuration. The GaInP/GaAs top cell was glued to eagle glass slide by transparent epoxy as shown in Fig. 6b. The top-cell area was calibrated of 0.25 cm^2. The SHJ bottom cell was also calibrated with 0.25 cm^2 cell area by sputtered ITO films as shown in Fig. 6a. In particular, it should be noticed that a long Ag-busbar of the bottom cell connected with screen-printed Ag-grid line at front side was designed outside the illuminated cell area and extended to the side for measurement-contacting, as shown in Fig. 6a. The back-side of the bottom cell was full-covered by screen-printed Ag as shown in Fig. 6c. Finally, the III-V/Si cell were formed by sticking the back-side glass with front side of the bottom cell as expressed in Fig. 6d.

The external quantum efficiencies (EQE) and J-V curves of the multi-junction III-V/Si solar cell are shown in Fig. 7. A total efficiency of 29.0% with 22.68% of III-V top cell and 6.35% of SHJ bottom cell was obtained by this structure. A further

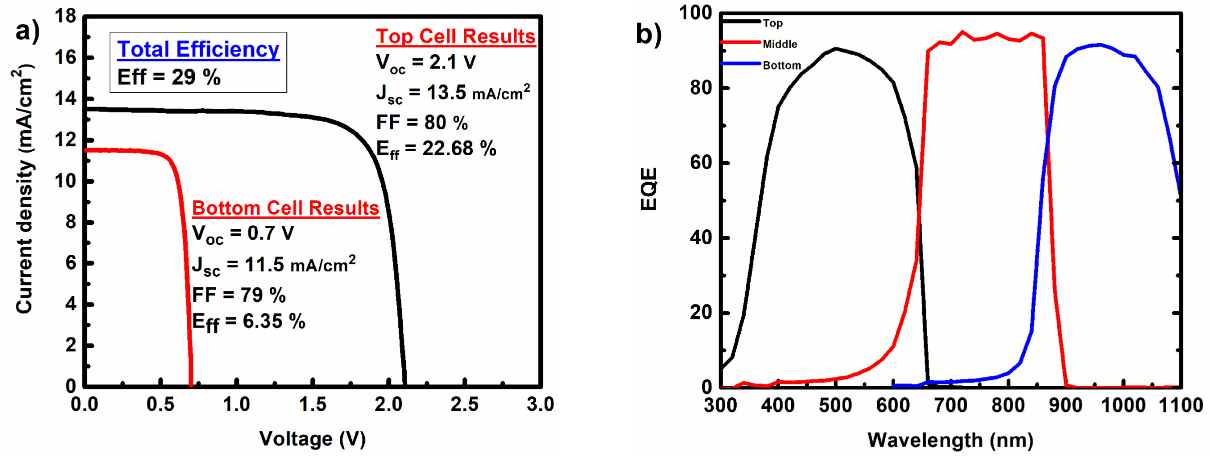

Fig. 7. a) J-V curves of III-V top cell and c-Si bottom cells of III-V/c-Si tandem solar cells, and b) EQE curves of separated cells in the tandem solar cells

improved performance can come from higher quality of III-V top cell or SHJ bottom cell and a high efficiency over 30% can be obtained as shown in Table 4. These results exceed the confirmed efficiency value of a SHJ single-junction as shown in Table 1 and even the theoretical efficiency limit of single SHJ bottom cell (29.4%). These really open a considerably potential path toward higher performances which is still continuously implementing with higher bandgap top cell materials or material quality improvements. A key challenge in development of the III-V/Si multi-junction solar cells is still effective commercial cell-price which can be competitive with III-V solar cells or SHJ single cells.

4. Conclusions

In this contribution, we present a brief review the state-of-art characteristics of wide-gap materials which has been potential as top cell for Si-based tandem solar cells. It shows that wide-gap GaInP and GaAs materials seem to be appropriate materials for Si-based multi-junction solar cells because they reveal effective light-conversion especially in the short wavelength below 650 nm. They indicated higher spectral efficiency than other ones such as CIZG, a-Si:H, perovskite, and CdTe. Consequently, we indicate the impress features of the III-V/Si multi-junction solar cells which has presently obtained the highest performance of 35.9% in Si-based multi-junction configuration. A four-terminal III-V/Si tandem solar cell structure implemented by our group is also addressed. The cell characteristic such J-V curves and EQE of this tandem are also conducted with high efficiency of 29.0% including 22.6% of III-V top cell and 6.8% of SHJ bottom cell. Compared with other top cell materials such as perovskite and a-Si:H, the III-V materials are achieving intensive attention for high efficiency of Si-based multi-junction solar cell in future because their achieved performance exceeds the theoretical efficiency limit of single SHJ bottom cell.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20188500000380).

References

1. Pham, D. P., Kim, S., Kim, S., Lee, S., Le, A. H. T., Park, J., Yi, J., "Ultra-thin stack of n-type hydrogenated microcrystalline silicon and silicon oxide front contact layer for rear-emitter silicon heterojunction solar cells," Materials Science in Semiconductor Processing, Vol. 96, pp. 1-7, 2019.
2. Holman, Z.C., Descoeudres, A., Barraud, L., Fernandez, F.Z., Seif, J.P., Wolf, S.D., Ballif, C.,"Current losses at the front of silicon heterojunction solar cells," IEEE J. Photovolt., Vol. 2, No. 1, pp. 7-9, 2012.
3. Taguchi, M., Kawamoto, K., Tsuge, S., Baba, T., Sakata, H., Morizane, M., Uchihashi, K., Nakamura, N., Kiyama, S., Oota, O., "HITTM Cells High Efficiency Crystaline Si Cels with Novel Structure," Prog. Photovolt. Res. Appl., Vol. 8, pp. 503-513, 2000.
4. Taguchi, M., Terakawa, A., Maruyama, E., Tanaka, M.. "Obtaining a higher Voc in HIT cells," Prog. Photovolt. Res.

Appl., Vol. 13, No. 6, pp. 481–488, 2005.

5. Yoshikawa, K., Kawasaki, H., Yoshida, W. *et al.*, "Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%," Nature Energy, Vol. 2, p. 17032, 2017.
6. Richter, A., Benick, J., Feldmann, F., Fell, A., Hermle, M., Glunz, S. W., "n-Type Si solar cells with passivating electron contact: Identifying sources for efficiency limitations by wafer thickness and resistivity variation," Sol. Energy Mater. Sol. Cells, Vol. 173, pp. 96-105, 2017.
7. Masuko, K., Shigematsu, M., Hashiguchi, T., Fujishima, D., Kai, M., Yoshimura, N., Yamaguchi, T., Ichihashi, Y., Mishima, T., Matsubara, N., Yamanishi, T., Takahama, T., Taguchi, M., Maruyama, E., Okamoto, S., "Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell," IEEE Journal of Photovoltaic, Vol. 4, No. 6, 2014.
8. Green, M., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E. D., "Solar cell efficiency tables (version 47)," Prog. Photovolt: Res. Appl., Vol. 24, pp. 3-11, 2016.
9. Green, M., Hishikawa, Y., Dunlop, E. D., Levi, D. H., Ebinger, J. H., Yoshita, M., Ho-Boillie, A. W. Y., "Solar cell efficiency tables (version 53)," Prog. Photovolt: Res. Appl., Vol. 27, pp. 3-12, 2019.
10. Cariou, R., Benick, J., Feldmann, F., Hohn, O., Hauser, H., Beutel, P., Razek, N., Wimplinger, M., Blasi, B., Lackner, D., Hermle, M., Siefer, G., Glunz, S. W., Bett, A. W., Dimroth, F., "III-V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration," Nature Engergy, Vol. 3, p. 326-333, 2018.
11. Essig, S., Allebe, C., Remo, T., Geisz, J. F., Steiner, M. A., Horowitz, K., Barraud, L., Ward, J. S., Schnabel, M., Descoeudres, A., Young, D. L., Woodhouse, M., Despeisse, M., Ballif, C., Tamboli, A., "Raising the one-sun conversion efficiency of III-V/Si solar cells to 32.8% for two junctions and 35.9% for three junctions," Nature Energy, Vol. 2, p. 17144, 2017.
12. Feifel, M., Ohlmann, J., Benick, J., Hermle, M., Belz, J., Beyer, A., Volz, K., Hannappel, T., Bett, A. W., Lackner, D., Dimroth, F., "Direct Growth of III-V/Silicon Triple-Junction Solar Cells with 19.7% Efficiency," IEEE Journal of Photovoltaics, Vol. 8, No. 6, p. 1590, 2018.
13. Almansouri, I., Ho-Baillie, A., Bremner, S. P., Green, M. A., "Supercharging Silicon Solar Cell Performance by Means of Multijunction Concept," IEEE Journal of Photovoltaics, Vol. 5, No. 3, p. 968, 2015.
14. Chiu, P. T., Law, D. L., Woo, R. L., Singer, S., Bhusari, D., Hong, W. D., Zakaria, A., Boisvert, J. C., Mesropian, S., King, R. R., Karam, N. H., "35.8% space and 38.8% terrestrial 5J direct bonded cells," Proc. 40th IEEE Photovoltaic Specialist Conference, Denver, pp. 11-13, June 2014.
15. White, T. P., Lal, N. N., Catchpole, K. R., "Tandem Solar Cells Based on High-Efficiency c-Si Bottom Cells: Top Cell Requirements for > 30% Efficiency," IEEE Journal of Photovoltaics, Vol. 40, No. 1, p. 208, 2014.
16. Kayes, B. M., Nie, H., Twist, R., Spruytte, S. G., Reinhardt, F., Kizilyalli, I. C., Higashi, G. S., "27.6% conversion efficiency, a new record for single-junction solar cells under 1 sun illumination," Proceeding of the 37th IEEE Photovoltaic Specialists Conference, 2011.
17. Kim, S., Hwang, S. T., Yoon, W., Lee, H. M., "High performance GaAs solar cell using heterojunction emitter and its further improvement by ELO technique. Paper 4CV.1.127," European Photovoltaic Solar Energy Conference, Munich, June 2016.
18. Yang, W. S., Noh, J. H., Jeon, N. J., *et al.*, "High-performance photovoltaic perovskite layers fabricated through intramolecular exchange," Science, Vol. 349, No. 6240, pp. 1234-1237, 2015.
19. Tan, H., Moulin, E., Si, F., Schüttauf, J., Stuckelberger, M.M Isabella, O., Haug, F., Ballif, C., Zeman, M., Smets, A.H.M., "Highly transparent modulated surface textured front electrodes for high efficiency multijunction thin film silicon solar cells," Prog. Photovolt., Vol. 23, pp. 949–963, 2015.
20. Fang, J., Ren, Q., Wang, F., Wei, C., Yan, B., Zhao, Y., Zhang, X., "Amorphous silicon/crystal silicon heterojunction double-junction tandem solar cell with open-circuit voltage above 1.5 V and high short-circuit current density," Sol. Energy Mater. Sol. Cells, Vol. 185, pp. 307-311, 2018.
21. Park, J., Dao, V. A., Kim, S., Pham, D. P., Kim, S., Le, A. H. T., Kang, J., Yi, J., "High efficiency Inorganic/Inorganic Amorphous Silicon/Heterojunction Silicon Tandem Solar Cells," Scientific Reports, Vol. 8, p. 15386, 2018.
22. Yu, Z., Leilaeioun, M., Holman, Z., "Selecting tandem partners for silicon solar cells," Nature Energy, Vol. 1, pp. 1-4, 2016.
23. Essig, S., *et al.*, "Wafer-bonded GaInP/GaAs//Si solar cells with 30% efficiency under concentrated sunlight," IEEE J. Photovolt., Vol. 5, pp. 977-981, 2015.
24. Bab, M., *et al.*, "Feasibility study of two-terminal tandem solar cells integrated with smart stack, areal current matching, and low concentration," Prog. Photovolt. Res. Appl., Vol. 25, pp. 255-263, 2017.
25. Lee K. H., *et al.*, "Assessing material qualities and efficiency limits of III-V on silicon solar cells using external radiative efficiency," Prog. Photovolt. Res. Appl., Vol. 24, pp. 1310-1318, 2016.
26. Chiu P. T., *et al.*, "35.8% space and 38.8% terrestrial 5J direct bonded cells," Proc. 40th IEEE Photovolt. Spec. Conf. (PVSC), 2014.
27. Dimroth F., *et al.*, "Four-junction wafer-bonded concentrator solar cells," IEEE J. Photovolt., Vol. 6, pp. 343-349, 2016.
28. Bolkhovityanov, Y. B., Pchelyakov, O. P., "GaAs epitaxy on Si substrates: modern status of reseach and engineering," Phys. Usp., Vol. 51, p. 437, 2008.
29. Grassman, T. J., Chmielewski, D. J., Carnevale, S. D., Carlin, J. A., Ringel, S. A., "GaAsP/Si dual-junction solar cells grown

by MBE and MOCVD," IEEE J. Photovolt., Vol. 6, pp. 326-331, 2016.

30. Essig S., *et al.*, "Wafer-bonded GaInP/GaAs//Si solar cells with 30.2% efficiency under concentrated sunlight," IEEE J. Photovolt., Vol. 5, pp. 977-981, 2015.
31. Gee, J. M., Virshup, G. F., "A 31% efficient GaAs/silicon mechanically stacked, multijunction concentrator solar cells," Proc. Conf. Record Twentieth IEEE Photovolt. Spec. Conf., 1988.
32. Howlader, M. M. R., Selvaganapathy, P. R., Deen, M. J., Suga, T., "Nanobonding technology toward electronic, fluidic, and photonic systems intergration," IEEE J. Sel. Top. Quantum Electron., Vol. 17, No. 3, pp. 689-703, 2011.