Scientific Research Publishing

Energy and Power Engineering, 2022, 14, 167-180
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Loss Analysis of High-Efficiency Perovskite/Si Tandem Solar Cells for Large Market Applications

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How to cite this paper: Yamaguchi, M., Nakamura, K., Ozaki, R., Kojima, N. and Ohshita, Y. (2022) Loss Analysis of High-Efficiency Perovskite/Si Tandem Solar Cells for Large Market Applications. *Energy and Power Engineering*, **14**, 167-180.
https://doi.org/10.4236/epe.2022.144009

Received: March 22, 2022
Accepted: April 26, 2022
Published: April 29, 2022

Abstract

The Si tandem solar cells composes of III-V, II-VI, chalcogenide and perovskite top cells and Si bottom cells are very attractive for creation of new markets. The perovskite/Si tandem solar cells are thought to be one of the most promising PV devices because of high-efficiency and low-cost potential. However, efficiencies of perovskite/Si tandem solar cells with an efficiency of 29.8% are lower compared to 39.5% with III-V 3-junction tandem solar cells and 35.9% with III-V/Si 3-junction tandem solar cells. Therefore, it is necessary to clarify and reduce several losses of perovskite/Si tandem solar cells. This paper presents high efficiency potential of perovskite/Si tandem solar cells analyzed by using our analytical procedure and discusses about non-radiative recombination, optical and resistance losses in those tandem solar cells. The perovskite/Si 2-junction tandem solar cells is shown to have efficiency potential of 37.4% as a result of non-radiative recombination loss of 2.3%, optical loss of 2.7% and resistance loss of 3.1%. Although the perovskite/Si 3-junction tandem solar cells are thought to be very attractive because of higher efficiency with an efficiency of more than 42%, decreasing non-radiative recombination loss in wide bandgap perovskite solar cell materials is pointed out to be necessary.

Keywords

Perovskite, Si Tandem Solar Cells, High-Efficiency, Loss Analysis

1. Introduction

The development of high-performance solar cells offers a promising pathway toward achieving high power per unit cost for many applications. Especially, photovoltaics-powered vehicle applications are very attractive for reducing CO_2 emission and creation of new market [1] [2] [3]. It is shown in our previous papers [1] [2] [3] that the high-efficiency solar cell modules have great impact upon CO_2 emission reduction, battery charging cost saving and driving distance increase of electric vehicles. Therefore, development of high-efficiency solar cell modules with an efficiency of more than 30% is very important. Various single-junction solar cells have been developed and efficiencies of 29.1% [4], 26.7% [5], 23.35% [6], 22.1% [4] and 22.6% [4] (small area efficiency of 25.5% [4]) have been demonstrated with GaAs, Si, CIGSe, CdTe and perovskite solar cells, respectively. However, single-junction solar cells may be capable of attaining AM1.5 efficiencies of up to 30% - 32% [7]. That is, state-of-the-art of single-junction solar cells is approaching the Shockley-Queisser limit [8]. An important strategy to raise the efficiency of solar cells is stacking solar cell materials with different bandgaps to absorb different colors of the solar spectrum. This so-called "multi-junction" (MJ) [7] [9] approach can efficient photon absorption and reduce thermalisation losses. This concept was most successfully implemented in III-V compound semiconductor solar cells, since compound semiconductors have a good range of lattice parameters and bandgaps to choose from them. As shown in **Figure 1**, high efficiencies of 32.9% [10], 39.5% [6], 38.8% [11] and 39.2% [12] under 1-sun illumination have been demonstrated with 2-junction, 3-junction, 5-junction and 6-junction solar cells, respectively. However, significant cost reduction in III-V compound solar cells is needed.

The Si tandem solar cells [13] composes of III-V, II-VI, chalcogenide and perovskite top cells and Si bottom cells are very attractive as high-efficiency and low-cost solar cells. The perovskite based tandem solar cells are thought to be

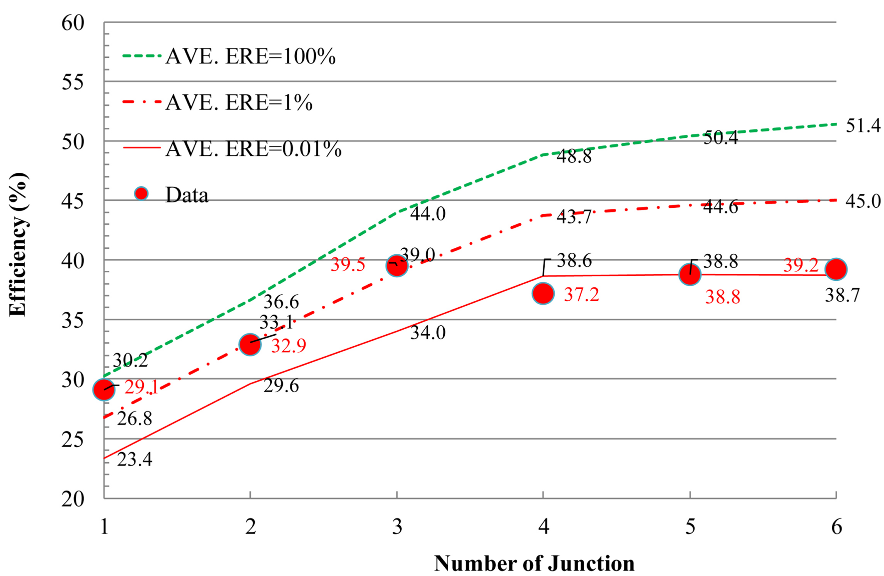

Figure 1. Multi-junction solar cells are very attractive for high-efficiency of more than 40%. Calculated an obtained efficiencies of multi-junction solar cells as a function of ERE and number of junction. ERE shows external radiation efficiency and the solar cells with the higher ERE value show the less of non-radiative recombination loss. (Reproduced with permission from Ref. 7 [AIP], [2021] and updated).

one of the most promising PV devices because of high-efficiency and low-cost potential. Although several approaches for perovskite based tandem solar cells are presented, efficiencies of perovskite based tandem solar cells (29.8% [4] with Perovskite/Si 2-junction, 26.4% [4] with perovskite/perovskite 2-junction and 24.6% [14] with perovskite/CIGS 2-junction, tandem solar cells) are lower compared to 39.5% [4] with III-V 3-junction and 35.9% [15] with III-V/Si 3-junction tandem solar cells. Therefore, it is necessary to clarify and reduce several losses of the perovskite based tandem solar cells.

This paper presents high efficiency potential of perovskite based tandem solar cells analyzed by using our analytical procedure [16] [17] [18] and discusses about non-radiative recombination, optical and resistance losses in those tandem solar cells. In this paper, the perovskite/Si 2-junction tandem solar cells is shown to have efficiency potential of 37.4% as a result of non-radiative recombination loss of 2.3%, optical loss of 2.7% and resistance loss of 3.1%. Regarding the perovskite/Si 3-junction tandem solar cells, high efficiency potential of more than 42% and necessity of reducing non-radiative recombination loss in wide bandgap perovskite solar cell materials are also discussed.

2. Analytical Procedure of High-Efficiency Potential of Tandem Solar Cells

One of the problems to attain the higher efficiency perovskite based tandem solar cells is to reduce non-radiative recombination loss. The open-circuit voltage V_{oc} drop compared to bandgap energy ($E_g/q - V_{oc}$) is dependent upon non-radiative voltage loss ($V_{oc,\,nrad}$) that is expressed by external radiative efficiency (*ERE*). Open-circuit voltage is expressed by [19]

$$V_{oc} = V_{oc,rad} + \frac{kT}{q}\ln\left(ERE\right) \tag{1}$$

where $V_{oc,\,rad}$ is radiative open-circuit voltage and 0.28 V [18] [20] for perovskite solar cells and 0.26 V [17] [20] [21] [22] for Si solar cells were used as $\Delta V_{oc,\,rad}$ (= $E_g/q - V_{oc,\,rad}$) in this study. The second term on the right-hand side of Equation (1) is denoted as $V_{oc,nrad}$ because it associates to the voltage-loss due to non-radiative recombination. In the case of multi-junction tandem solar cells, we define average *ERE* (ERE_{ave}) by using average V_{oc} loss [23]:

$$\Sigma\left(V_{oc,n} - V_{oc,rad,n}\right)/n = \left(kT/q\right)\ln\left(ERE_{ave}\right), \tag{2}$$

where n is the number of junctions.

The resistance loss of a solar cell is estimated solely from the measured fill factor. The ideal fill factor FF_0, defined as the fill factor without any resistance loss, is estimated by [24]

$$FF_0 = \left(v_{oc} - \ln\left(v_{oc} + 0.72\right)\right)/\left(v_{oc} + 1\right), \tag{3}$$

where v_{oc} is [24]

$$v_{oc} = V_{oc}/\left(nkT/q\right). \tag{4}$$

The measured fill factors can then be related to the series resistance and shunt resistance by the following equation [24]:

$$FF \approx FF_0\left(1-r_s\right)\left(1-r_{sh}^{-1}\right) \approx FF_0\left(1-r_s-r_{sh}^{-1}\right) = FF_0\left(1-r\right), \tag{5}$$

where r_s is the series resistance, and r_{sh} is the shunt resistance normalized to characteristic resistance R_{CH}. The characteristic resistance R_{CH} is defined by [24]

$$R_{CH} = V_{oc}/J_{sc}, \tag{6}$$

r is the total normalized resistance defined by $r = r_s + r_{sh}^{-1}$.

3. Analytical Results for High-Efficiency Potential of Perovskite Based Tandem Solar Cells

Figure 2 shows calculated and obtained 1-sun efficiencies of perovskite/Si [4], perovskite/perovskite [14] and perovskite/CIGS [4] 2-junction solar cells in comparison with those of III-V 3-junction [4], 2-junction [10], III-V/Si 3-junction [15] and III-V/Si 2-junction [15] tandem solar cells. Although 29.8% [4], 26.4% [4] and 24.2% [4] have been achieved with perovskite/Si, perovskite/perovskite and perovskite/CIGS 2-junction tandem solar cells, those efficiencies are lower than 39.5% [4] and 32.9% [4] with III-V 3-junction and 2-junction solar cells. Figure 2 suggests that perovskite based tandem solar cells have larger non-radiative loss compared to those of III-V 3-junction and 2-junction solar cells and further improvements in efficiency are thought to be possible by improving ERE. The ERE values estimated in this study are 0.116% for 29.8% [4] and 0.109%

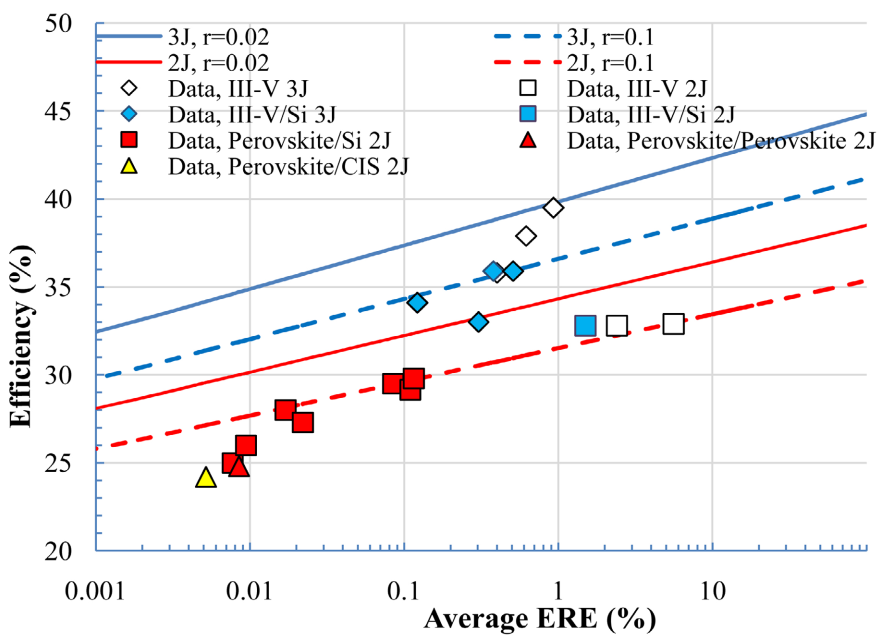

Figure 2. The Si tandem solar cells have potential efficiencies of 36% and 42% with 2-junction and 3-juction tandem solar cells. Calculated and obtained 1-sun efficiencies of perovskite/Si, perovskite/perovskite and perovskite/CIS 2-junction solar cells in comparison with those of III-V 3-junction, 2-junction, III-V/Si 3-junction, III-V/Si 2-junction tandem solar cells.

for 29.15% [25] perovskite/Si, 0.0085% for 24.2% [4] perovskite/perovskite and 0.0074% for 24.2% [4] perovskite/CIGS 2-junction tandem solar cells that are lower compared to 0.93% for 39.5% [4] and 0.62% for 37.9% [25] III-V 3-junction, 0.51% for 35.9% [15] III-V/Si 3-junction, 5.6% for 32.9% [4] III-V 2-junction and 1.5% for 32.8% [15] III-V/Si 2-junction tandem solar cells. **Figure 2** shows that the 2-junction and 3-junction tandem solar cells have potential efficiencies of more than 36% and 42%, respectively.

Figure 2 suggests that improving ERE by reduction in non-radiative recombination loss of sub-cells is very important in order to realize higher efficiency multi-junction solar cells. Because ERE values decrease with increase number of junctions and those in Si tandem solar cells are lower than those in III-V multi-junction solar cells, improvements in material quality of sub-cells and reduction in interface recombination are necessary.

In addition, resistance loss of tandem solar cells including inter-connection loss is discussed in this study. **Figure 3** shows correlation between fill factor and resistance loss r ($r_s + 1/r_{sh}$) in InGaP, GaAs, Si, CdTe, CIGS and perovskite single-junction solar cells, and various 2-junction and 3-junction tandem solar cells. Resistance loss of CIGS and perovskite single-junction solar cells composing of multi-component materials is higher than InGaP, GaAs, Si and CdTe single-junction solar cells. In general, resistance losses of tandem solar cells increase with number of junctions by inheriting resistance loss of single-junction solar cells. That means, reduction in resistance loss of sub-cells is neccesary. Reduction in series resistance of interconnection of sub-cells is necessary in order to

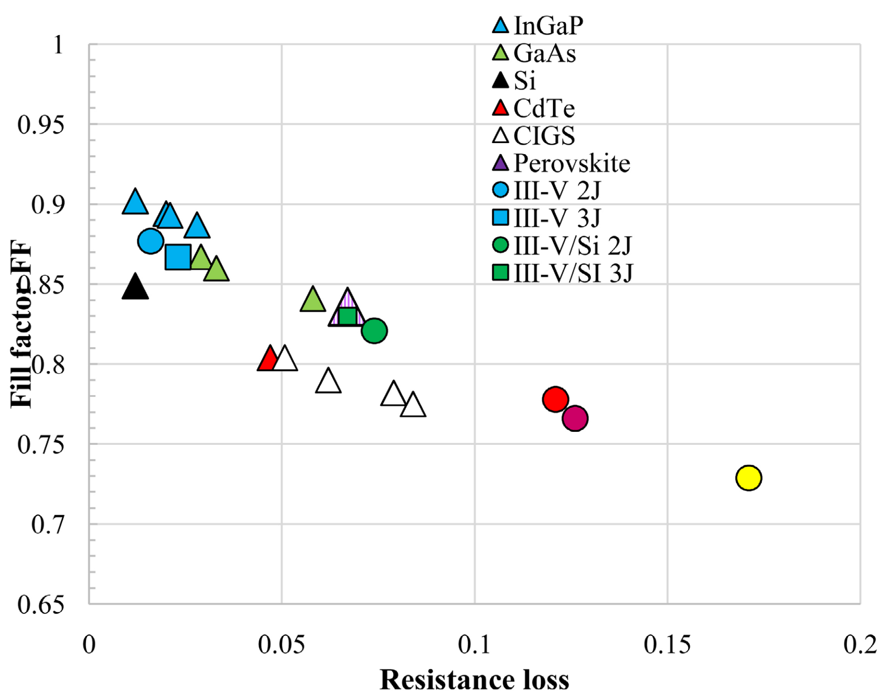

Figure 3. Reduction in resistance loss is necessary for high-efficiency. Correlation between fill factor and resistance loss in InGaP, GaAs, Si, CdTe, CIGS, and perovskite single-junction solar cells, and various 2-junction and 3-junction tandem solar cells.

improve tandem cell properties. Optimization of interconnections of sub-cells is very important because interconnection layer sometimes reduces short-circuit current density of bottom cells due to optical transmission loss in addition to resistance loss.

4. Discussion about Further Efficiency Improvements of Perovskite Based Tandem Solar Cells

In this section, loss elements for the various perovskite based tandem solar cells are discussed. Practical limiting efficiencies estimated by assuming ERE of 10%, optical loss of 5% and resistance loss of 2% were 28.8% for single-junction, 36.4% for 2-junction and 42.4% for 3-junction solar cells. Recombination loss was estimated by using Voc values and Equations (1) and (2), optical loss was estimated by using Jsc values and photon flux as a function of bandgap energy, and resistance loss was estimated by using FF and Equation (5).

Figure 4 shows summary of loss elements for the various single-junction, 2-junction and 3-junction solar cells calculated and the present efficiencies obtained. The values shown here are absolute conversion efficiency and absolute efficiency loss. The efficiency of multi-junction tandem solar cells in practical limit was calculated by assuming ERE of 10%, optical loss of 5% and resistance loss of 2%. In the case of GaAs single-junction solar cells, ERE of 30% was assumed because ERE of 22.5% has been obtained for GaAs [20] [21]. Here, some comments are shown.

1) Although 22.6% efficiency was obtained with perovskite single-junction solar cells [4], there are still efficiency improvements of 1.9% by recombination

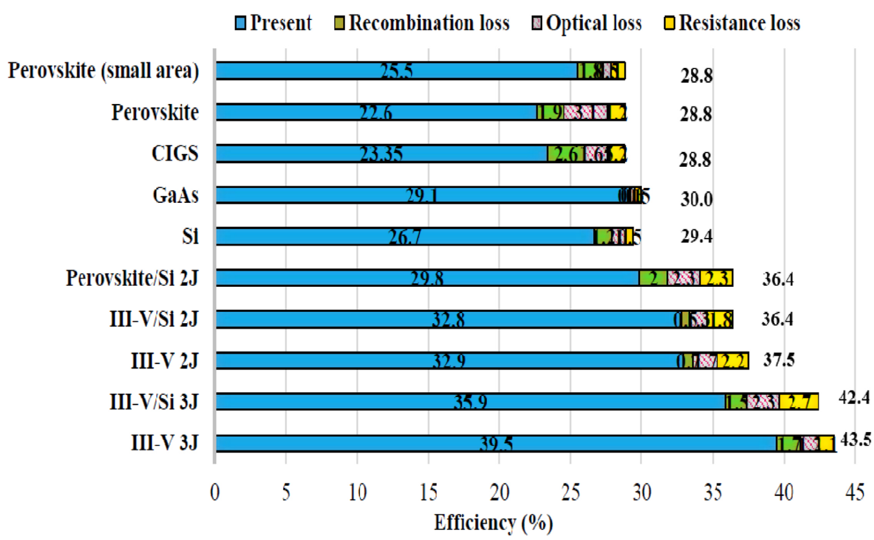

Figure 4. Reduction in non-radiative, optical and resistance losses is necessary for realizing high-efficiency of more than 36% and 42% with 2-junction and 3-junction tandem solar cells. Summary of loss elements for the various single-junction, 2-junction and 3-junction solar cells calculated and the present efficiencies obtained. The values shown here are absolute conversion efficiency and absolute efficiency loss.

loss reduction, 3.1% by optical loss reduction and 1.2% by resistance loss reduction. In order to realize higher efficiency, reduction in non-radiative recombination loss and effective utilization of photon recycling are recommended,

2) The 2-junction solar cells have higher potential efficiency of 36.4%. For example, althigh efficiency of perovskite/Si 2-junction solar cells obtained is 29.8% [4], there are still 6.9% efficiency improvement potential with 2%, 2.3% and 2.3% by reduction in recombination loss, optical loss and resistance loss, respectively. In the case of perovskite/CIGS 2-junction solar cell [4], there are still 12.2% efficiency improvement potential with 5.9%, 2.2% and 4.0% by reduction in recombination loss, optical loss and resistance loss, respectively.

3) Because 3-junction solar cells have higher potential efficiency of 42.4%, development of high-efficiency perovskite based 3-junction solar cells is very attractive.

Bandgap energy combination of sub-cells is one of key issues for realizing high-efficiency multi-junction solar cells. **Table 1** shows optimum bandgap energy combination for high-efficiency multi-junction solar cells reported by Philipps and Bett [26]. In the case of III-V compound based multi-junction solar cells, material selection of sub-cells has been made by considering availability of substrate, lattice matching between sub-cell layers and substrate and material growth process. Bandgap energy combination for 37.9% III-V 3-junction solar cell [27] is 1.90/1.42/0.98 eV. Regarding 38.8% III-V 5-junction solar cell [11], bandgap energy combination is 2.17/1.68/1.40/1.06/0.73 eV. Bandgap energy combination for 39.5% III-V 6-junction solar cell [12] is 2.19/1.76/1.45/ 1.19/0.97/0.70 eV.

The Si tandem solar cells [13] consisting of III-V, II-VI, chalcopyrite and perovskite top cell and Si bottom cell are attracting a great deal of attention because of high-efficiency and low-cost potential. Optimum bandgap energy combination for high-efficiency Si tandem solar cells was calculated [28] [29]. **Figure 5** shows calculated efficiency in radiative limit of Si tandem solar cells as a function of number of junctions. The efficiency of Si tandem solar cells in radiative limit was calculated by assuming ERE of 100%, optical loss of 5% and resistance loss of 2%. High efficiency of 45.2% and 49.6% is expected with 2-junction solar cell and 3-junction solar cells. Because optimum bandgap energy

Table 1. Optimum bandgap energy combination for high-efficiency multi-junction solar cells.

Number of junction	Optimum bandgap energy combination
1	1.34 eV
2	1.60/0.93 eV
3	1.90/1.37/0.93 eV
4	2.00/1.49/1.11/0.72 eV
5	2.14/1.67/1.33/1.01/0.70 eV
6	2.19/1.73/1.41/1.13/0.79/0.51 eV

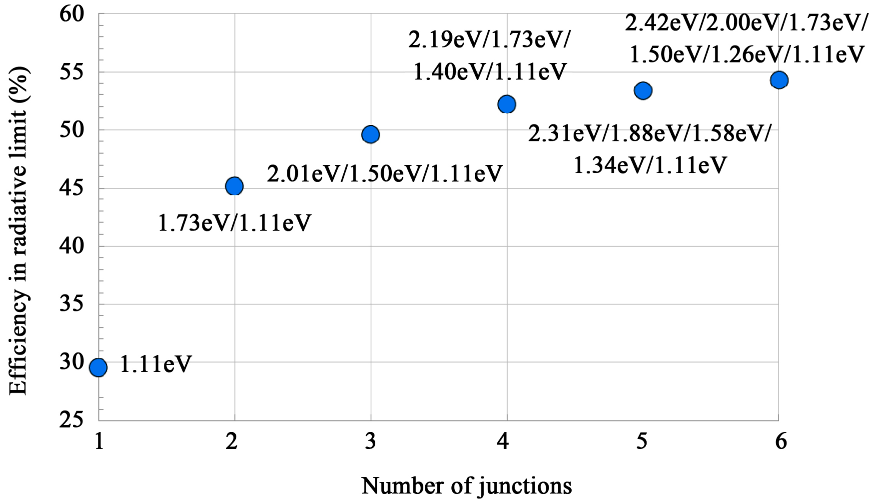

Figure 5. Optimum bandgap energy combinatin of Si tandem solar cells for realizing high-efficiency Si tandem solar cells. Calculated efficiency in radiative limit of Si tandem solar cells as a function of number of junctions.

combination is 1.73 eV/Si(1.11 eV) and 2.01 eV/1.50 eV/Si(1.11 eV), optimization of bandgap energy for perovskite perovskite/Si tandem solar cells is necessary.

High-efficiency perovskite 2-junction solar cells have been demonstrated with an efficiency of 29.15% [25] by using 1.68 eV $Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}Pb(I_{0.77}Br_{0.23})_3$/Si 2-junction tandem solar cell, an efficiency of 24.2% [30] by using 1.68 eV $Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}Pb(I_{0.77}Br_{0.23})_3$/1.1 eV CIGS 2-junction tandem solar cell, an efficiency of 24.8% [31] by using 1.77 eV $Cs_{0.2}FA_{0.8}Pb(I_{0.6}Br_{0.4})_3$/1.22 eV $MA_{0.3}FA_{0.7}Pb_{0.5}Sn_{0.5}I_3$ 2-junction tandem solar cell. Although development of perovskite based 3-junction tandem solar cells is very attractive for various applications, there are many candidate materials for perovskite based 3-junction tandem solar cells. **Figure 6** shows changes in bandgap energy of various perovskite materials for 3-junction and Si 3-junction tandem solar cells as a function of composition and optimum bandgap energies by summarizing some review paper [31] [32] [33] [34] [35] for perovskite/Si, perovskite/CIGS and all perovskite 2-junction tandem solar cells.

Candidate materials for 3-junction solar cells are listed as follows:

Top cell (1.90 eV): $CsPb(I_{1-x}Br_x)_3$, $MAPb(I_{1-x}Br_x)_3$, $FAPb(I_{1-x}Br_x)_3$, $CsMAFAPb(I_{1-x}Br_x)_3$,

Middle cell (1.37 eV): $MAPb_xSn_{1-x}I_3$, $FAPb_xSn_{1-x}I_3$,

Bottom cell (0.93 eV): $CsSnI_3$, $MASnI_3$, $FASnI_3$,

Candidate materials for Si 3-junction tandem solar cells are listed as follows:

Top cell (2.01 eV): $CsPb(I_{1-x}Br_x)_3$, $MAPb(I_{1-x}Br_x)_3$, $FAPb(I_{1-x}Br_x)_3$, $CsMAFAPb(I_{1-x}Br_x)_3$,

Middle cell (1.50 eV): $MAPb_xSn_{1-x}I_3$, $FAPb_xSn_{1-x}I_3$, $CsMAFAPb_xSn_{1-x}I_3$,

Bottom cell (1.11 eV): Si.

Figure 7 shows changes in open-circuit voltage Voc as a function of bandgap energy of various perovskite materials by summarizing some papers [32] [33]

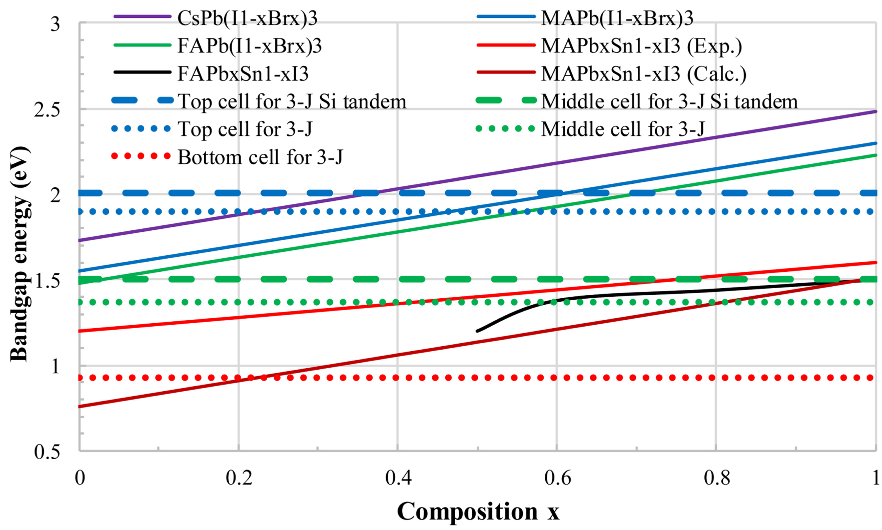

Figure 6. Optimum bandgap energies and candidate perovskite materials for realizing high-efficiency perovskite based 3-junction tandem solar cells. Changes in bandgap energy of various perovskite materials for 3-junction and Si 3-junction tandem solar cells as a function of composition and optimum bandgap energies by summarizing some review paper [31] [32] [33] [34] [35] for perovskite/Si, perovskite/CIGS and all perovskite 2-junction tandem solar cells.

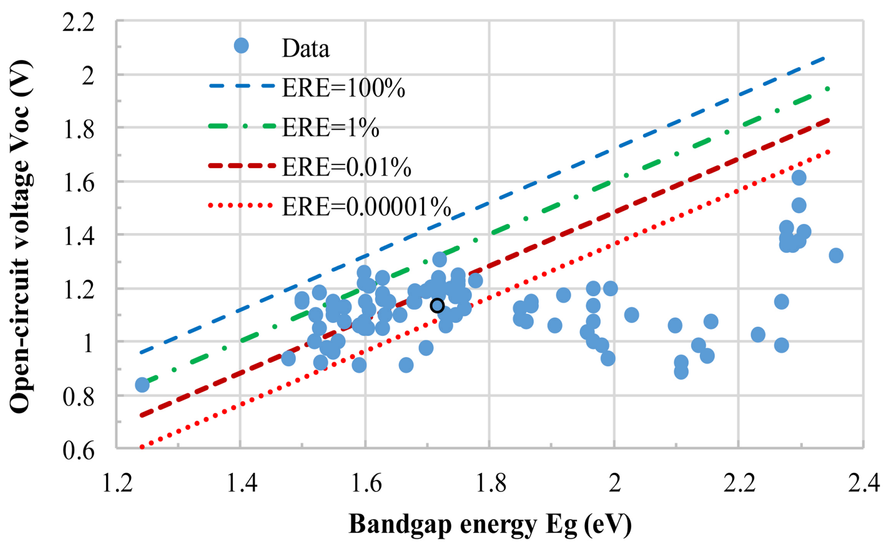

Figure 7. Decreasing non-radiative recombination in wide bandgap perovskite materials is important for realizing high-efficiency perovskite based tandem solar cells. Changes in open-circuit voltage Voc as a function of bandgap energy of vari ous perovskite materials by summarizing some papers [32] [33] [35] [36] [37] and external radiative efficiency ERE.

[35] [36] [37] and external radiative efficiency ERE. Although $MAPbI_3$ and other perovskite materials with bandgap energy of 1.5 - 1.7 eV have higher ERE values of more than 1% as shown in **Figure 7**, wide-gap perovskite materials show lower ERE values of less than 0.01%. Several approaches for Si tandem solar cells are expected to realize practical limiting efficiencies 36% and 42% for 2-junction

Table 2. Current and future efficiency potential of the perovskite/Si 3-junction tandem solar cells. Current ERE values of candidate top cell, middle cell and bottom cell materials for perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells and potential efficiencies calculated by using current ERE values and ERE = 10%.

Perovskite 3-junction cell		Top cell (1.90 eV)	Middle cell (1.37 eV)	Bottom cell (0.93 eV)	Average ERE	Estimated Efficiency (Current ERE)	Potential Efficiency (ERE = 10%)
	ERE	4.4×10^{-6} %	0.8%	?	1.88×10^{-3} %		
	Efficiency					31.9%	44.9%
Perovskite/Si 3-junction cell		Top cell (2.01 eV)	Middle cell (1.50 eV)	Bottom cell (Si)	Average ERE	Estimated Efficiency (Current ERE)	Potential Efficiency (ERE = 10%)
	ERE	2.2×10^{-7} %	0.46%	1.32%	5.19×10^{-3} %		
	Efficiency					33.3%	42.3%

and 3-junction Si tandem solar cells.

In this study, potential efficiencies of perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells were calculated by using current ERE values and ERE = 10% and analytical procedure described in Section 3. Table 2 shows current ERE values of candidate top cell, middle cell and bottom cell materials for perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells and potential efficiencies calculated by using current ERE values and ERE = 10%. Because wide-bandgap perovskite materials show low ERE values of less than 10^{-6} % and average ERE values of around 10^{-3} % with for perovskite based 3-junction tandem solar cells, possible efficiencies estimated for perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells are 33.1% and 34.2%, respectively. If high-quality perovskite materials with average ERE value of 10% are developed, high-efficiencies of 44.9% and 42.3% are expected to realized with perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells as shown in Table 2.

5. Summary

High-efficiency (>30%) solar cells are very important for reducing CO_2 emission and creation of new market such photovoltaics-powered vehicles. The perovskite based tandem solar cells are very attractive for such a purpose. This paper presented analytical results for efficiency potential and loss elements of perovskite based tandem solar cells. The 2-junction and 3-junction tandem solar cells have potential efficiencies of 36% and 42%, respectively by improving ERE (external radiative efficiency), and reducing resistance and optical losses.

In this paper, loss elements of perovskite based tandem solar cells were discussed. Although efficiency of perovskite/Si 2-junction solar cells obtained is 29.5%, there is still 6.9% efficiency improvement potential with 2%, 2.3% and 2.6% by reduction in recombination loss, optical loss and resistance loss, respectively. In the case of perovskite/CIGS 2-junction solar cell, there is still 12.2% efficiency improvement potential with 5.9%, 2.2% and 4.0% by reduction in recombination loss, optical loss and resistance loss, respectively.

Development of high-efficiency perovskite based 3-junction and perovskite/Si 3-junction tandem solar cells is very attractive for many applications because of higher efficiency potential of 44.9% and 42.3%. Further understanding nature of defects in perovskite materials and decreasing non-radiative recombination loss in wide bandgap perovskite solar cell materials is pointed out to be necessary. Optimization of bandgap energy and reduction in optical loss and electrical loss of interconnection of sub-cells are also very important.

Acknowledgements

This work has been partially supported by NEDO (New Energy and Industrial Technology Development Organization). The authors thank members in the NEDO and JST (Japan Science and Technology Agency), and to Dr. K-H. Lee and Dr. K. Araki, former Toyota Tech. Inst., Dr. F. Dimroth and Mr. P. Schygulla, FhG-ISE for their cooperation and providing fruitful information.

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations Conflict of Interest

The authors state that there is no conflict of interest.

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