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

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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

Jsc : short-circuit current density, (mA/cm²)
Voc : 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. In addition, the reduction of surface-recombination loss as well as losses due to metal/semiconductor contact have been attended. Consequently, the world record cell efficiency reaching over 25% and even 26.7% have been achieved recently by various research groups. 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. 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. These imply that the high efficiency development for...
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

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

<table>
<thead>
<tr>
<th>Single-junction structure</th>
<th>Cell efficiency (%)</th>
<th>Cell area (cm(^2))</th>
<th>Year</th>
<th>Group/Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBC</td>
<td>26.7</td>
<td>79</td>
<td>2017</td>
<td>Kaneka(^9)</td>
</tr>
<tr>
<td>TOPCon</td>
<td>25.7</td>
<td>4</td>
<td>2017</td>
<td>Fraunhofer(^6)</td>
</tr>
<tr>
<td>HIT rear junction</td>
<td>25.6</td>
<td>143.7</td>
<td>2014</td>
<td>Panasonic(^7)</td>
</tr>
<tr>
<td>IBC</td>
<td>25.2</td>
<td>153.49</td>
<td>2012</td>
<td>SunPower(^8)</td>
</tr>
<tr>
<td>p-type POLO-IBC</td>
<td>26.1</td>
<td>3.9857</td>
<td>2018</td>
<td>ISFH(^9)</td>
</tr>
<tr>
<td>p-type PERC</td>
<td>25.0</td>
<td>4</td>
<td>1998</td>
<td>UNSW(^9)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Top cell material</th>
<th>Band Gap (eV)</th>
<th>Cell efficiency (%)</th>
<th>Cell area (cm(^2))</th>
<th>Group/Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs (thin film)</td>
<td>1.5</td>
<td>28.8</td>
<td>0.99</td>
<td>Alta devices(^{16})</td>
</tr>
<tr>
<td>GaInP</td>
<td>1.82</td>
<td>21.4</td>
<td>0.25</td>
<td>LG electronics(^{17})</td>
</tr>
<tr>
<td>II-V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>1.5</td>
<td>22.1</td>
<td>0.47</td>
<td>First solar(^9)</td>
</tr>
<tr>
<td>CZTS</td>
<td>1.8</td>
<td>11.0</td>
<td>0.23</td>
<td>UNSW(^9)</td>
</tr>
<tr>
<td>Perovskite</td>
<td>1.6</td>
<td>22.7</td>
<td>0.09</td>
<td>KRICT(^{16})</td>
</tr>
<tr>
<td>Si (amorphous thin film)</td>
<td>1.7</td>
<td>10.2</td>
<td>1.0</td>
<td>AIST(^9)</td>
</tr>
<tr>
<td>CIGS (thin film)</td>
<td></td>
<td>22.9</td>
<td>1.0</td>
<td>Solar frontier(^9)</td>
</tr>
</tbody>
</table>
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:

\[
\eta(\lambda) = V_{oc} \cdot FF \cdot J_{sc}(\lambda) / I(\lambda),
\]

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

\[
J_{sc}(\lambda) = q \cdot \lambda \cdot EQE(\lambda) \cdot I(\lambda) / (h \cdot c),
\]

with $q$ and $h$ are elementary charge and Planck’s constant, respectively; $EQE(\lambda)$ 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

![Graph showing 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.](image1)

![Figure 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).](image2)
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.
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. 422). 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 wavelength22). As a results, their tandem structure will lead to less performance than the bottom cell alone22). 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 TSSCs23). 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 performance23). 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 systematically23). 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 nm23). Experimentally, a high efficiency of over 30% has been achieved by many research groups with III-V/c-Si MJSSCs21,12,22). Table 3 summaries some recent results for MJSSCs22). 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 years23-25). 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 illumination26) and 46% for a four-junction under concentrated illumination27). 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 MJSSCs28), have been proposed in recent years29). 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 bonding30) or mechanical staking31). 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 nm32), and clean room environment while the mechanical staking eliminates these

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

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

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.
requirements and thus offers a lower-cost solution\(^\text{11}\).

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

### 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

<table>
<thead>
<tr>
<th>Top cell material</th>
<th>Bandgap (eV)</th>
<th>Efficiency (%)</th>
<th>Year</th>
<th>Group/institute</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>III-V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlGaAs</td>
<td>1.6</td>
<td>25.2</td>
<td>2012</td>
<td>Univ. Tokyo</td>
<td>Two-terminal; fusion bonding</td>
</tr>
<tr>
<td>AlGaAs</td>
<td>1.6</td>
<td>21.2</td>
<td>1998</td>
<td>Nagoya Inst. Tech.</td>
<td>Two-terminal; epitaxial growth</td>
</tr>
<tr>
<td>GaInP</td>
<td>1.8</td>
<td>29.8</td>
<td>2016</td>
<td>NREL</td>
<td>Four-terminal; mechanical stack</td>
</tr>
<tr>
<td>II-VI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdZnTe</td>
<td>1.8</td>
<td>16.8</td>
<td>2010</td>
<td>EPIR Tech</td>
<td>Two-terminal; epitaxial growth</td>
</tr>
<tr>
<td>Perovskite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH(_3)NH(_3)PbI(_3)</td>
<td>1.6</td>
<td>19.2</td>
<td>2016</td>
<td>EPFL</td>
<td>Two-terminal; direct deposition</td>
</tr>
<tr>
<td>CH(_3)NH(_3)PbI(_3)</td>
<td>1.6</td>
<td>22.8</td>
<td>2015</td>
<td>EPFL</td>
<td>Four-terminal; mechanical stack</td>
</tr>
<tr>
<td>CH(_3)NH(_3)PbI(_3)</td>
<td>1.6</td>
<td>28.0</td>
<td>2015</td>
<td>Kaneka</td>
<td>Four-terminal; optical coupling</td>
</tr>
<tr>
<td>CH(_3)NH(_3)PbBr(_3)</td>
<td>2.3</td>
<td>23.4</td>
<td>2015</td>
<td>UNSW</td>
<td>Four-terminal; optical coupling</td>
</tr>
</tbody>
</table>

**Fig. 5.** Schematic diagram of III-V/c-Si MJSSC with GaInP/GaAs 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
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.

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References


