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New Generation Multijunction Solar Cells for Achieving High Efficiencies

Sunhwa Lee[1)] · Jinjoo Park[1)] · Youngkuk Kim[1)] · Sangho Kim[2)] · S. M. Iftiquar[1)] · Junsin Yi[1,2)]*

[1)]School of Information and Communication Engineering, Sungkyunkwan University, Suwon 16419, Korea
[2)]Department of Energy Science, Sungkyunkwan University, Suwon 16419, Korea

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ABSTRACT: Multijunction solar cells present a practical solution towards a better photovoltaic conversion for a wider spectral range. In this review, we compare different types of multi-ijunction solar cell. First, we introduce thin film multijunction solar cell include to the thin film silicon, III-V material and chalcopyrite material. Until now the maximum reported power conversion efficiencies (PCE) of solar cells having different component sub-cells are 14.0% (thin film silicon), 46% (III-V material), 4.4% (chalcopyrite material) respectively. We then discuss the development of multijunction solar cell in which c-Si is used as bottom sub-cell while III-V material, thin film silicon, chalcopyrite material or perovskite material is used as top sub-cells.

Key words: Tandem solar cells, Multijunction solar cells, Thin film solar cell, c-Si solar cell

Nomenclature

AM1.5G : standard solar radiation of 100mW/cm^2 intensity.
PCE : power conversion efficiency
V_{oc} : open circuit voltage
J_{sc} : short circuit current density
FF : fill factor
HJ-IBC : Heterojunction-Interdigitated back Contact
PV : photovoltaic
a-Si:H : Amorphous silicon
μc-Si:H : micro-crystalline silicon
TRJ : tunnel-recombination junction
DSSC : Dye-sensitized solar cells
CIGS : Copper indium gallium selenide
a-SiC:H : hydrogenated amorphous silicon carbide

1. Introduction

Crystalline silicon solar cell is one of the oldest and most widely used devices until now. There are various reasons for its popularity, few of them are large scale availability, low level pollution and the device performance is relatively stable. However, limitation of c-Si solar cell is it lower output voltage. In order to overcome this limit, several different device structures have been proposed and work is continuously going on to improve its efficiency further[1)]. Silicon solar cells have occupied nearly 80 to 90% of the entire market of the photovoltaics[2)]. In order to achieve higher efficiency, new device structures in combination with various other factors have been derived, for example HJ-IBC was developed by Kaneka in 2017, achieving 26.7% device efficiency[3)]. Recent advances in commercial single junction PV technologies are approaching a practical and theoretical limits of efficiency. Raising optical absorption by introducing various light trapping schemes is one of the factors. Tandem or multi-junction solar cells can be another alternative to maximize optical absorption of solar spectra. The key requirements for a high efficiency tandem solar cell are: 1) high efficiency of the top sub-cell with a wider bandgap materials, 2) compatibility with the lower cell and current matching, and 3) optimization of the tunnel-recombination junction (TRJ). Optimized multi-junction solar cells that combine low bandgap and high bandgap materials can have theoretical efficiency of as high as 44% in a tandem structure under 1 sun illumination[4)]. Fig. 1 shows approximate division of absorption spectra among the top and bottom sub-cells in a tandem solar cell. Low-cost multijunction solar cells have been studied based on thin film solar cells. Typical examples are amorphous and microcrystalline silicon solar cells[5-7)] and Ⅲ-Ⅴ compound solar cells. Dye-sensitized solar

*Corresponding author: junsin@skku.edu

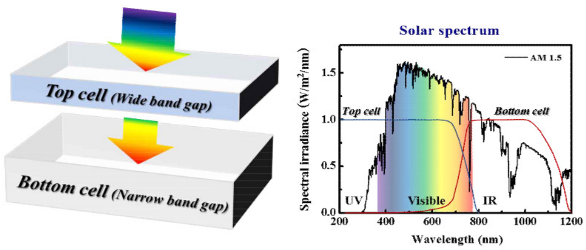

Fig. 1. Schematic of multijunction solar cells having different band gaps and solar spectrum

Table 1. Multijunction thin film silicon solar cell efficiencies measured under 1 sun or the global AM 1.5 spectrum at 25°C

	Eff (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Institute (Year)
Tandem	12.00	1.330	12.92	68.5	AIST[5] (2012)
	12.63	1.382	12.82	71.3	IMT[6] (2014)
	12.69	1.342	13.45	70.2	AIST[11] (2015)
Triple	12.41	1.936	8.96	71.5	United solar[7] (2011)
	13.44	1.963	9.52	71.9	LG[12] (2013)
	13.60	1.901	9.92	72.1	AIST[13] (2015)
	14.00	1.922	10.39	73.4	AIST[14] (2016)

cells (DSSC), organic solar cells, and quantum dot solar cells are being studied as low cost tandem solar cells, and hybrid structures such as DSSC / CIGS, organic / thin film silicon are also being studied.

2. Thin Film Tandem Solar Cells

2.1 Thin Film Silicon Devices

Starting from 1983[8], various research groups have developed multijunction solar cell in which cells with multiple band gaps are connected in series to increase the efficiency of silicon solar cells. This type of devices can absorb solar spectra more efficiently than single junction solar cells[9] and may have less light induced degradation[10].

Various schemes have also been proposed to improve stability under light induced degradation[6,15,16], for example, by using graded band gap active layer[16], silicon oxide interlayer[17], or electron cyclotron resonance chemical vapor deposition.[(15)] United Solar Systems corp. reported development of a-Si:H/ μc-Si:H/ μc-Si:H triple junction smaller solar cells with efficiency of 12.41% and efficiency of 400 cm^2 sized device as 11.7%.[11] Improved light trapping can raise device efficiency further. The AIST group in Japan reported an a-Si:H/μc-Si:H/μc-Si:H triple junction solar cell with an efficiency of 14.04% on a honeycomb-textured SiO_2 substrate[7]. Various works are going on to improve device efficiency further by adopting various other surface textures[18], bifacial structure, gradient band gap active layer[19], buffer layers[9] and improving materials[20,21]. In a two terminal tandem device tunnel and recombination junction is also another important factor to influence device performance[22].

2.2 III-Vmaterial Based Devices

The III-V compound materials used in solar cells are direct bandgap materials, so these materials have high optical absorption coefficients. Epitaxial layer growth technique can be implemented with a variety of band gap that is suitable for multi junction solar cells. Furthermore, these compound semiconductors have excellent temperature stability and reliability at a high-temperature. It exhibits higher photovoltaic conversion efficiency under concentrated radiation and is therefore suitable for a power generation system under a highly concentrated radiation. Soitec, CEA-Leti and Fraunhofer ISE reported gallium indium phosphide (GaInP)/ gallium arsenide (GaAs); gallium indium arsenide phosphide (GaInAsP)/ gallium indium arsenide (GaInAs) four-junction solar cells of 46% efficiency at a 50.8 W/cm^2 radiation that is concentrated by a factor of 508 of the solar spectrum[23]. NREL reported an advanced four-junction inverted metamorphic (4J IMM) cell, consisting of lattice mis-matched GaInP/ GaAs/ GaInAs/ GaInAs layers. The cell efficiency of 45.7% and 45.2% was measured under 234 and 700 suns concentrated radiations respectively[23].

2.3 Chalcopyrite Material Based Devices

The band gap of chalcopyrite materials is tunable from 1.02 eV ($CuInSe_2$) to ~1.68 eV ($CuGaSe_2$)[24-26]. The chalcopyrite based tandem solar cells have been investigated for more than 30 years[27]. A single junction cell can have a lower efficiency like ~7% but in a tandem device structure with GaAs can have higher efficiency like 23.1% in outer atmosphere (under AM0 insolation). In order to obtain high quality chalcopyrite properties, a high temperature process of 350°C[28] or above[29] is required. However, the device characteristics degrade rapidly because of inter-diffusion of contaminating atoms like Cu[30], especially when the top cell process proceeds at over 200C. For this reason, most of the studies are concentrated on fabrication by mechanically stacking the sub-cells. Development of Ag(In,Ga)Se / Cu(In,Ga)Se_2 was reported by Nakada et al.[31] It was a two terminal mechanically stacked tandem cell, with an AIGS top cell fabricated on ITO back contact (Eff = 6.6%) IMO back contact (Eff = 8%) with filtered Cu(In,Ga)Se_2 bottom cell. The key issue with chalcopyrite based tandem solar cells is the development of high efficiency top cell with good optical transmission. The theoretical optimum bandgap of the CIS based tandem cell is 1.72 eV for the top cell and 1.14 eV for the bottom cell. In 2010, Kaigawa et al.[32] demonstrated a 4.4% efficiency Cu(In,Ga)S_2/ Cu$InSe_2$ tandem solar cell with an open circuit voltage of 1.08 eV.

3. Silicon Wafer Based Tandem Solar Cells

The multijunction solar cell utilizing the existing high-efficiency c-Si technology has become a reliable commercial product[2]. In combination with different other semiconductor materials, high efficiency silicon multi junction solar cell is possible. For example, theoretical efficiency of GaAs/GaAs/Si solar cell can possibly be 33%[33]. `Tomas P. W. et al reported tandem solar cells based on c-Si sub-cell of efficiency above 30%[34]. They modeled the efficiency of low-cost thin-film top cells suitable for high-efficiency c-Si bottom cells, and investigated

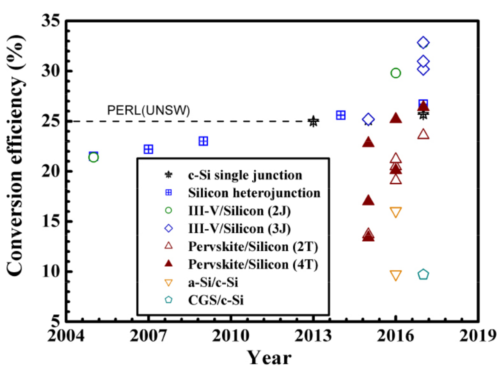

Fig. 2. efficiencies for various PV technologies including single junction c-Si solar cell[3,35,36] and silicon wafer based multijunction solar cell

the effect of band gap, absorption coefficient, diffusing length and luminescence efficiency on top cell[34].

Fig. 2 shows the highest experimental cell efficiencies reported in the literature for single junction c-Si solar cell and c-Si bottom cell based multijunction solar cell.

3.1 III-V Material as Top Cell

III-V materials is a useful material for top cell because of its high band gap and good optoelectronic properties. A multijunction solar cell with III-V material based top sub-cell and c-Si based bottom sub-cell can have a theoretical efficiency of 33%[33]. In recent years, performance of III-V solar cells on Si have greatly improved due to the deposition using metalorganic vapor phase epitaxy (MOVPE). However, epitaxial growth of III-V on the Si substrate increases the density of structural defects and lowers the minority carrier lifetime due to mismatch of lattice constant and thermal expansion coefficient. In 1997, T. Soga et al demonstrated a 21.4% efficiency metalorganic chemical vapor deposition (MOCVD) growth AlGaAs/Si 2J solar cell with four-terminal configuration[37].

The multijunction solar cell efficiency of more than 25% can only be achieved if the two cells are fabricated separately and combined at a lower temperature with wafer bonding or mechanical stacking. Essig et al. demonstrated a 29.8% efficiency GaInP/Si 2J solar cell with silicon heterojunction (SHJ) bottom cell in 4-terminal operation conditions[38]. The wafer-bonded GaInP/AlGaAs//Si 3J solar cells developed by Fraunhofer ISE[40], which were optimized for two-terminal operation and in which the III-V and Si subcells are connected by tunnel junctions. It recently reached record effciency of 32.3%, as presented at a conference[41]. EPFL, IMT, CSEM PV-center and NREL developed 32.5% and 32.8% III-V/Si multijunction solar cells based on

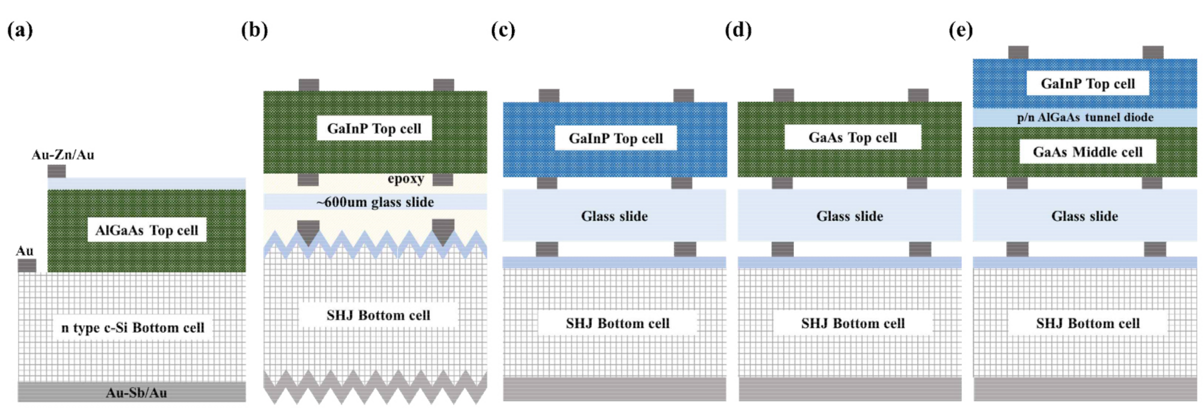

Fig. 3. Design Of The Iii-V/Si Multijunction Solar Cell. (A) Epitaxial Growth Of Iii-V On C-Si Bottom Cell[19] (B) Mechanical Stacking 2J Cell[20] (C)-(E) Wafer-Bonded Gainp/Si 2J , Gaas/Si 2J And Gainp/Gaas//Si 3J Cell[23]

mechanical stacking of 1.81 eV GaInP and 1.42 eV GaAs top cells, respectively, on SHJ bottom cells. It resulted to 35.9% efficient Si-based triple junction solar cell featuring a monolithic GaInP/GaAs 2J top cell on SHJ bottom cell with a thicker front TCO.[39] Fig. 3 shows four-terminal GaInP/GaAs//Si triple junction solar cell.

3.2 Thin Film Silicon and Chalcopyrite Material as Top Cell

According to the modeling of White et al.[34], the maximum efficiency of a tandem cell is 29.5% when CIS or CZTS is used as the top cell, and it is 31.8% in case of a-Si:H or Sb_2S_3 as the top cell. The optical bandgap of chalcopyrite and the a-Si:H materials are easy to adjust, and are therefore used as the top cell of the multijunction solar cell when a good quality and high efficiency c-Si bottom sub-cell is used[34].

In this context, the sungkyunkwan university is developing this type of high efficiency a-Si:H/HIT type tandem solar cell, where n/p type tunnel recombination junction plays an important role (Fig. 4)[22]. Although the earlier reported efficiency was low but continuous effort shows a significant improvement in device efficiency[42].

In 2014, Guijun et al studied a nanopyramide structure for ultrathin a-Si/c-Si tandem solar cells with efficiency of 13.3%[43]. Jinjoo et al could realize an efficiency of 16.04%. They developed a monolithic tandem using a Si-Ge/Si tandem junction solar cell with MgF_2 anti-reflection coating[42].

Uzu et al developed a wide band gap a-Si top and HIT bottom cell with optical splitting system. The optical splitting system is positioned 45° with respect to both cell in Fig. 5. The short wavelength is reflected to the top cell and the long wavelength is transmitted to the bottom cell. The a-Si top cell efficiency is 5.1% and HIT bottom cell efficiency is 19.9% with splitting system. A combination of a widegap amorphous thin film silicon solar cell and a HIT cell were test-coupled via an optical beam splitter. Although it is not exactly a tandem cell, but the reported efficiency of this combined solar cells were over 25%[44].

The KIST reported a 9.7% c-Si/ITO/CGSe monolithic tandem solar cells based on cell-selective light absorption[45]. In the case of a-Si:H cells, the required thickness of the absorber layer is low, and therefore can have a higher optical transmittance, so that a higher device efficiency can be expected through optimization of device structure. The 4-terminal multijunctional solar cell based on chalcopyrite material, made by mechanical stacking, etc., can also be expected to exhibit high device efficiency.

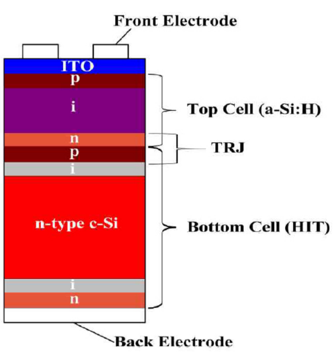

Fig. 4. Schematic diagram of a-Si:H/HIT type tandem solar cell[22]

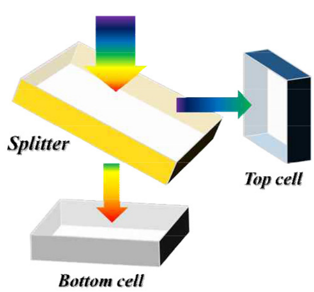

Fig. 5. Schematic image of the optical splitting system[44]

3.3 Perovskite as Top Cell

Organometal halide perovskite solar cells were first reported to have 3.8% efficiency in 2009[46], but its recently reported value is 20.3% in 2018[47], making it an attractive material for solar cell[46,48]. The perovskite materials also has the advantage of easy band gap control and simple deposition process. There are many reports about perovskite / silicon multijunction solar cells. In 2015, Mailoa et al. first studied 2-terminal perovskite / silicon multijunction solar cells (Fig. 6(a))[49]. The efficiency was 13.7% through bottom cell using n-type silicon wafer based doping process and perovskite top cell using TiO_2 and 2,2',7,7'-Tetrakis (N,N-di-4-methoxyphenylamino)-9,9'-spirobifluorene (spiro-OMeTAD). Werner et al developed a perovskite / silicon multijunction solar cell with an efficiency of 21% at an aperture area of 0.17 cm^2 (Fig. 6(b))[50]. They used bottom cell of planar (non-texture) HIT structure and perovskite cell of top cell used electron transport layer of polyethylenimine (PEIE) / phenyl-C_{61}-butyric-acid-methyl-ester (PCBM) bilayer and spiro-OMeTAD was used as the hole transport material. At present, the reported efficiency of tandem cell is 26.4% when 23.6% efficient HIT cell was used[51]. By combining recently developed cesium formamidinium lead halide perovskite and infrared-tuned HIT bottom cell with passivated front and rear surfaces and rear side texturing (Fig. 6(c))[52]. In 2014, Wang et al.[53] reported

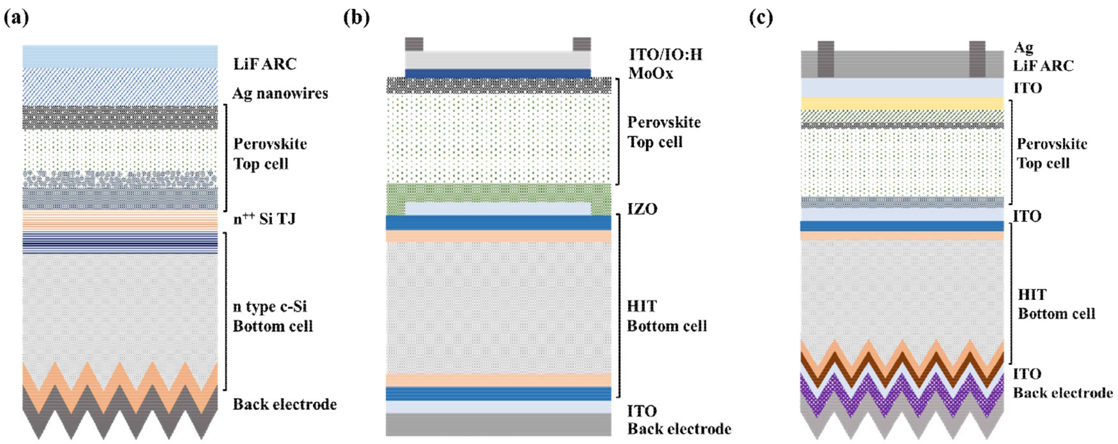

Fig. 6. Schematic of the perovskite/silicon tandem solar cell (not to scale). (a) Structure redrawing from Mailoa et al.[31)] (b) Structure redrawing from Werner et al.[32)] (c) Structure redrawing from Bush et al.[33)]

mechanically stacked perovskite/ silicon multijunction solar cell with an efficiency of 17%. The top cell is standard FTO/ TiO_2/ perovskite/ Spiro-OMeTAD structure and bottom cell had 11.4% effective-efficiency of multi-crystalline silicon solar cell. A 4-terminal perovskite/ silicon multijunction solar cell with an estimated efficiency of 31.6%[54)] was reported. Another similar cell, using textured HIT bottom cell was reported to show efficiencies as 25.2% and 23% for 0.25 cm^2 and 1 cm^2 areas, respectively[55)]. Uzu et al developed a perovskite top cell and HIT bottom cell with optical splitting system. The optical splitting system was shown Fig. 5. The multijunction solar cell is a standard FTO/ TiO_2/ $MAPbI_3$/ Spiro/ Au top cell with a HIT bottom cell. The multijunction solar cell efficiency of 28% was reported by Uzu et al.[44)]

4. Conclusions

In this article, we reviewed few of the multijunction solar cell technologies: thin film based and c-Si based multijunction solar cell are more promising to compete with the c-Si single junction in efficiency. Multijunction solar cell has shown broader spectral band-width for optical absorption, as well as high device efficiency. It is also expected that the multijunction solar cells will have better stability than that of a single junction device.

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