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Current Status of High-efficiency a-Si/c-Si Heterojunction Solar Cells: A Review

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ABSTRACT Heterojunction with intrinsic thin film (HIT) is a stable and efficient device because it blends the strength of crystalline silicon and amorphous silicon. The cells can be produced at low temperatures, usually below 200°C, which decreases the thermal budget and allows the use of thinner wafers, resulting in a decrease in production cost. Heterojunction silicon solar cells use silicon substrates for both absorption and transport, and a microcrystalline or amorphous thin layer of silicon for the purpose of junction and passivation formation. The top electrode is composed of a metal grid and transparent conductive oxide (TCO). Heterojunction solar cells have attracted considerable attention because they achieve efficiencies up to 26.3, which is close to the theoretical efficiency. The low-temperature process allows the handling of silicon substrates less than 100 μm in thickness with a high yield. The main characteristic is the use of metal contacts in this technology, which are extremely recombination active in conventional diffused junctions, and can be distinguished from the absorber through the introduction of a layer with a wide band gap. A high open circuit voltage is generally achieved with heterojunction devices without the need for valuable patterning technology.

Key words Transparent conductive oxide, High efficiency, Surface passivation, Heterojunction solar cell

Nomenclature

V_{oc} : open circuit voltage, mV
J_{sc} : Short circuit current, mA/cm^2
FF : fill factor
η : efficiency
T : temperature
q : charge
k : boltzman
D_p=D_n : diffusion constant for holes and electron
S_p=S_n : Interface recombination velocity
C_p=C_n : capture rate coefficient for holes and electron
g : average photo generated of electron-hole pairs
τ_{eff} : effective lifetime of the excess carriers
J_{sat} : saturation current
$J_{sat\text{-}it}$: saturation current of interface recombination
P_{it} : hole concentration at the heterointerface
n_{it} : electron concentration at the heterointerface
A : diode identity factor
I_{ph} : photo current
I_o : Reverse saturation current
Φ_B : effective barrier for recombination at the heterojunction

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N_v : effective densities of state in the conduction band of $\delta_{Si(n)}$

N_c : effective denities of state in the conduction band of $\delta_{Si(p)}$

Subscript

HIT : heterojunction intrinsic thin film
TCO : transparent conductive oxide
PV : photovoltaics
SHJ : silicon heterojunction
MIS : metal-insulator-semiconductor
FF : fill factor
IBC-SHJ : inter digitated back contact silicon heteojunction
IZO : indium zinc oxide
ZnO : zinc oxide
ITO : indium tin oxide

1. Introduction

The basic principle of photovoltaics (PV) is to direct conversion of energy of solar radiation to electricity. PV is appealing a huge industrial and academic interest and can be considered the most predicting candidate for energy generation in future. In a solar cell, the energy conversation takes place in semiconductor materials such as silicon. Silicon becomes dominant PV technology because it shows good stability, well–balanced set of electronics, chemical, physical properties and economic benefits[1].

In the early 1950s, first diffused p–n junction based on p–type silicon device had around 4.5% of efficiency and since then, the improvement in conversion efficiency had started[1]. The efficiency of a cell has been ameliorated close to the theoretical limit of around 29%[2]. Higher energy conversion is shown by n–type crystalline silicon[3~5]. Heterojunction solar cells consist of crystalline silicon for light absorption and carrier transport, and amorphous or intrinsic thin layer for passivation and junction formation Transparent conductive oxide (TCO) is used as a top electrode. Because of high efficiency up to 25% and low–temperature process round about below then 200°C, silicon heterojunctions have a lot of intentions. Silicon–based heterojunction solar cells (Si–HJT) are a hot topic within crystalline silicon photovoltaic as it allows for solar cells with record–efficiency energy conversion up to 26.6%[6].

The concept of heterojunction solar cells (SHJ) was introduced by the company SANYO in 1992 by using crystalline and amorphous silicon[7]. The heterojunction cell is compiled of the individual thin wafer of silicon (c–Si) which is enclosed by the extremely thin layer of (a–Si: H) and both p–type and n–type doped amorphous silicon layer as shown in Fig. 1, that can be deposited by low temperature near about at 200°C. Transparent conducting oxide (TCO) layers and electrode are synthesized on the doped layers with the help of sputtering and screen–printing, respectively.

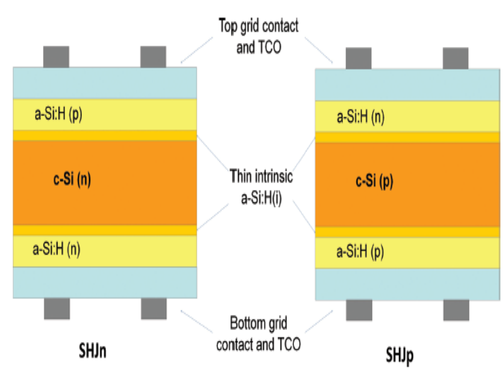

Fig. 1. Silicon heterojunction solar cells with a p–type silicon (SHJp) and n–type silicon (SHJn) HIT solar cell

2. The Heterojunction Concept

The key success of silicon heterojunction devices is the detachment of a crystalline surface from the recombination-active contact by the introduction of passivating film having wider band gap[8]. A layer which is called a buffer layer worked as a membrane that allows some specific carrier to be passed[9]. The interface state density of the silicon surface should be minimal. The SHJ concept exhibits an affinity with metal-insulator-semiconductor (MIS) cells that can be explained by the concept of quantum mechanics tunneling via buffer layer[10]. For buffer layer, the use of hydrogenated amorphous silicon (a-Si: H) with the thickness of just a few nm is much attracting and their band gap is wider than c-Si and process of doping can be easy[11]. The first heterostructure was examined in 1974 by Fuhs and coworkers[12]. Intrinsic a-Si: H films are remarkable in passivation of the c-Si surface which was spread after a few years later[13]. In the meantime, Hamakawa and their coworker reported high-efficiency a-Si solar cells in 1983 which was well-known n as honeymoon cell[14,15]. The junction between the two doped layers named as c-Si and a-Si: H is called an electronic junction which was progressively investigated at the same time[16,17]. Sanyo in 1980, began to merge the c-Si wafer with the concept of heterojunctions[18]. The first device having an efficiency close to 12% which was composed by the thin boron-doped a-Si: H and n-type c-Si wafer. These solar cells showed marginally fill factors (FF), that was activated more devices characterization. A huge breakthrough was observed by the introduction of the thin buffer layer which was undoped a-Si: H in between silicon wafer and boron doped a-Si: H emitter that called Heterojunction intrinsic thin layer (HIT) structure and this structure added the efficiency up to 14.5%[18]. Generally, the intrinsic layer enables to achieve high value for V_{oc} and maximum efficiency of SHJ solar cell. By using the heterostructure like passivating back contact encouraged the overall solar efficiency to 18%[19]. This result emphasizes the importance of heterostructure contact on the back-end side of the cell. Outline of a-Si: H/c-Si solar cell having rear and front coating of buffer layers, as shown in Fig. 2.

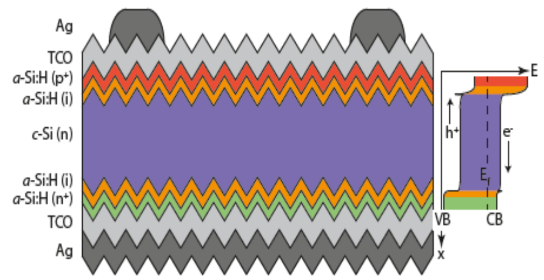

Fig. 2. Sketch of SHJ solar cell as first developed by Sanyo, Japan, admitting its band diagram

After a long time, the excess of efficiency reported by Sanyo which was round about 23.7%[20]. Recent result was received on wafer thickness of 98 μm, which is almost half of the industrial standard solar cells with diffused-junction. From a processing view, a big advantage of SHJ technology is the complete development of passivated a-Si: H films, having a low temperature less than 200°C.

The first diffused junction was formed in c-Si solar by using the n-type c-Si. The community rapidly followed the p-type substrate just for the ameliorated radiation hardness[21]. Yet the standard material to fabricate c-Si solar cell was p-type c-Si, as well as for market. In spite of this, the n-type wafer based on Czochralski (Cz) is used nowadays for achieving high-efficiency solar cells (*Use ITRPV report as a reference*).

First, the cost is powerfully determined by the purity of wafer, Therefore, in the case of same concentration of impurity, the minority carrier lifetime is less in p-type material as compared to the n-type counterpart[22]. Secondly, light-socking may damagingly impact of p-type material by oxygen and boron[23] or iron and boron[24] complexes. The n-type Cz material is choosing for the practiced devices rather than more costly, but the other option is a float zone (FZ) wafer, which contains less oxygen concentration and improved wafer quality. The favored material for the device's purpose of SHJ is mono– instead of multi–crystalline Si. The other main reason is low–temperature processing serving for SHJ cells, where average photo generated of electron–hole pairs (g) no processing accelerated bulk silicon wafer improvement can be anticipated from impurity gettering[25] and defect hydrogenation[26]. A good quality material having a millisecond lifetime should be applied from start. The wafer having better–defined surface is Mono–crystalline wafer.

Usually, silicon substrates are adapted for solar cell fabrication. Crystal texturing depends on the atomic density of crystal orientation, Pyramids on the face side of silicon (111) are anisotropically etched in alkaline solution[27,28]. The textured silicon surface helps to improve the internal reflection[29,30]. Importantly, the pyramids permit uniform deposition of nanometer thickness s–Si: H film by PECVD technique and thick TCO layer by PVD technique. For example, a layer of a–Si: H on pyramidally textured silicon is close to 1.7 times thinner than that of deposited film for flat silicon surface[31]. It is impossible to achieve the

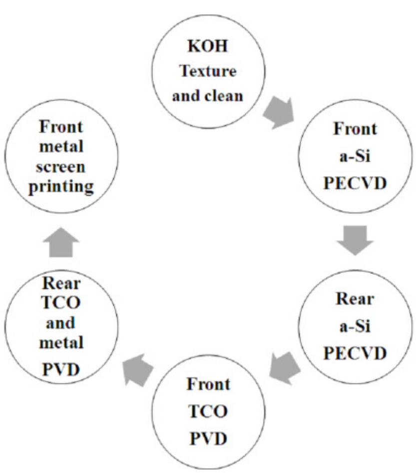

Fig. 3. Basic process steps for SHJ devices

uniform layer on the isotropically etched surface, which has U–shaped valleys[32]. The full sequence of device fabrication is shown in Fig. 3.

3. Relevant Design Parameters for SHJ Cell

In ideal solar cell, the carriers are generated by the photons, named as the photo–generated carriers that occupy the sufficiently time period in the process of absorber, so it can drift/diffuse to the contacts whereas the carrier is accumulated without the loss through recombination at its surface or in absorber's bulk as shown in Fig. 4(a). Contacts, which are selective regarding the carrier, can generate asymmetric potential barriers that the most of carries are collected with no any interference when the induced carriers are refused as shown in Fig. 4(b). In general, solar cells are synthesized to achieve the idealized configuration for attaining the efficient extraction of photo–generated carriers. Solar cells are divided into 3 categories according to the charge extraction:

1. "Diffused homojunction solar cells", this was used as commercial diffused silicon solar cell.
2. "Heterojunction solar cell", for example, thin film solar cells, CdTe and SHJ silicon wafer based solar cells.
3. "P–i–n homojunction solar cells" for instance a–Si: H thin film solar cells.

Generally, the solar cell is composed of diffused homojunction and the carriers move toward their relevant contact through diffusion. To be effective, this procedure takes extensive carrier diffusion and have a lofty standard of PV absorber. A heavily doped region is used for contact with respect to the type of doping to attain the carrier selectivity but to accomplish low resistivity contact as shown in Fig. 4(c). In spite of that such contacts, significant electrical losses are created at the time of doping which causes trouble in band gap narrowing and as well as optical losses. The p-i-n homojunction solar cell concept is to use of low price PV absorbers that are highly faulty, that lead toward the shorter diffusion length of the carrier as compared with the absorber thickness. For the case of photo-generated charge carriers, that is directly distinguished along the generation of intrinsic absorber layer below the work of the electric field. Because of absorber having a bad quality, the recombination at contact is normally not determining factor as shown in Fig. 4(d). P-i-n homojunction[33] and diffused solar cells[34~36] have studied in details. Design of cells; depend on defective materials or impurity doping, leads to a limitation in the desired efficiency of solar cell based on structure[37].

The heterojunction solar cell technology requires more than two dissimilar materials as shown in Fig. 4(e). This heterojunction solar cell describes in detail in this article.

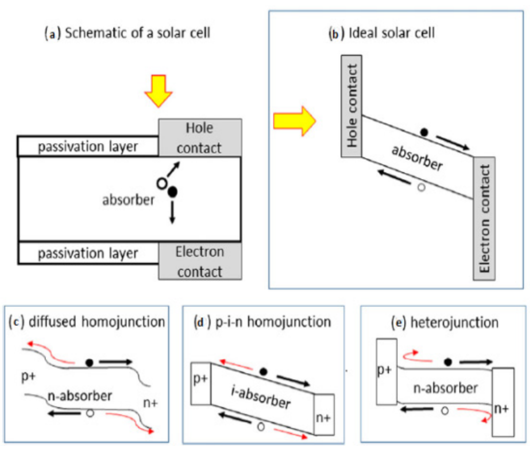

Fig. 4. Schematic of solar cell structures with energy band diagram: (a) schematic of a photo-generated carrier, (b) ideal solar cell, (c) diffused homojunction, (d) p-i-n homojunction, (e) and heterojunction

The performance of the solar cell is explained by J_{sc}, V_{oc}, and FF. These factors are engaged with efficiency η and explain overall yield execution of cells. The principal focus of this paragraph is to explain the heterointerface and inversion at the a-Si:H/c-Si and open circuit voltage V_{oc}, which influences by carrier transport and recombination properties in solar cells. The open circuit voltage V_{oc} can be describe as[38,39]

$$V_{oc} = \frac{nkT}{q} \ln\left[\frac{I_{ph}}{I_o} + 1\right] \approx \frac{nkT}{q} \ln\left[\frac{I_{ph}}{I_o}\right] \quad (1)$$

where q is elementary charge, T temperature, k Boltzmann constant, is the photon current and is the reverse saturation current. Other symbols refer the interface recombination for electrons $S_n = C_n D_{it}$ and for holes $S_p = C_p D_{it}$, where C_n and C_p are capture cross section for electrons and holes, D_{it} is represented the defect density. $\Delta p = \Delta n = g.\ \tau_{eff}$, this equation represents the surplus carries concentration and g represent the average photogeneration for electron-hole pairs in τ_{eff} and c-Si of the excess carriers.

The saturate current of SHJ, j_{sat}, is find out with help of saturation current of recombination j_{sat-it}, that is for SHJp decided along the recombination velocity S_n, and holes concentration at the heterointerface p_{it} as

$$J_{sat-it} = qS_p P_{it} \quad (2)$$

Similarly, by conceiving the interface of electron $n$it for SHJn it can be scripted

$$J_{sat-it} = qS_n n_{it} \quad (3)$$

By taking into the record the equation for V_{oc}

$$V_{oc} = \frac{AkT}{q} \ln\left[\frac{J_{sc}}{J_{sat}}\right] \quad (4)$$

And replacing j_{sat-it}, it is potential to script equation that finds the V_{oc} as a function of And replacing j_{sat-it}, it is potential to script equation that finds the V_{oc} as a function of recombination velocity and effective barrier for recombination at heterointerface Φ_B[40].

$$V_{oc} = \frac{\Phi_B}{q} - \frac{AkT}{q}\ln\left[\frac{qN_vS_p}{J_{sc}}\right] \quad (5)$$

For SHJp and

$$V_{oc} = \frac{\Phi_B}{q} - \frac{AkT}{q}\ln\left[\frac{qN_cS_n}{J_{sc}}\right] \quad (6)$$

For SHJn, A corresponds the diode ideality factor. The equation is given above, apparently show that V_{oc} is decided by Φ_B that having big data to find high V_{oc}.

4. Current Trends in SHJ Solar Cell Development

To construct SHJ solar cell more economical appealing, current attempts are concentrated on two important objectives, which are (i) decreasing the cost of fabrication (ii) increasing the efficiency. Larger band gap emitters like amorphous silicon carbide (a-SiC: H)[41], micro-crystalline Si oxide (μc-SiOx: H)[42] or nanocrystalline Si oxide (nc- SiOx: H)[43] were studied to enhance the J_{sc} by lowering parasitic light absorption and thereby lower the manufacturing cost. The enhance in J_{SC} approximately 1 mA/cm^2 was manifested by changing a-Si: H to a-SiC: H[44]. The second way to reduce the absorption loss is established on the synthesis of two contacts for the purpose of photo-generated carrier collection at the backside of the silicon wafer working as an inter-digitated back contact silicon heterojunction (IBC-SHJ) cells. Having the good result of accumulation electrodes at the back side of a cell are exhibited the most proficient efficiency of 25.6% currently accomplished at SHJ solar cells[45]. By eliminating the losses regarding absorption of a-Si: H layers and besides in TCO, the high J_{SC} = 41.8 mA/cm^2 is attained.

The diminishing in synthesis price can be accomplished through the alternate of valuable materials by much lower price options. Different research groups have inquired the second option material like indium zinc oxide (IZO)[46] or zinc oxide (ZnO)[47] as an alternative material of costly indium tin oxide (ITO). The replacing the silver with copper for collection electrodes is another method to decrease the cost of SHJ[48]. The reduction of the thickness of silicon wafer is also another approach to make solar cell more economical. The achievement of high performance with the using of the silicon wafer of very thin thickness is already reported in 2009. Nowadays a new approach is rising, which is based on replacing the emitter having an amorphous state with the metal oxides[49~51]. Such conception has the power to allow a decrease of cost during synthesis and increase the efficiency. Moreover, the different oxide, which is used as a deposition layer, is carried out at a low temperature which further decreases the fabrication cost and thermal budget.

Table 1 shows the result of SHJ devices which is published by a different research group working on this topic. By studying the table, one easily understands the emerging power of solar cells globally. Many research groups are now achieving more 20% efficiency. Outstandingly most of the research labs accomplish their best result using the 200 μm thick wafer. The record of Sanyo's is to synthesise a device by using just 98 μm thick wafer. Excellent passivation is done a-Si: H, and thanks for a thin wafer that give the

Table 1. Shows the efficiencies of HIT solar cells

Affiliation	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	h (%)	Year	Ref
Ideal cell (110 ㎛)	761	43.3	89.3	29.4	2016	[52]
Kaneka Corporation, Japan	738	42.65	84.9	26.7	2017	[53]
Panasonic	740	41.8	82.7	25.6	2014	[54]
SunPower Corporation	737	41.3	82.7	25.2	2016	[55]
Kaneka Corporation	738	40.8	83.5	25.1	2015	[56]
Univ. of new South Wales	706	42.7	82.8	25	2009	[57]
Panasonic	750	39.5	83.2	24.7	2014	[58]
Sanyo	745	39.5	80.9	23.7	2011	[59]
EPFL MoOx SHJ	725	38.6	80.4	22.5	2015	[60]
Kaneka Corporation	729	38.5	79.1	22.1	2011	[61]
RRS	735	38.5	77.5	21.9	2011	[62]
ERFL	721	37.8	79.7	21.8	2011	[63]
HHI	721	36.6	79.9	21.1	2011	[64]
CEA-INES	732	36.9	78.3	21	2011	[65]
CIC	685	36.9	79.2	20	2011	[66]

value of V_{oc} for the device as around 745 mV that is the biggest achievement of any single c-Si cell.

5. Conclusions

This paper was dedicated to SHJ solar cells with an intention to elaborate the effect of heterointerfaces on open circuit voltage V_{oc} and the yield of SHJn and SHJp solar cells. Carrier inversion was shown as the main role in SHJ solar cells for open circuit voltage and the resultant execution. Different attributes striking the carrier inversion were examined with the help of various simulations running towards the different results. Low defect state and band offset for the minority carriers in heterojunction solar cells is essential to accomplish high V_{oc} and strong carrier inversion. With the introducing of various simulations running towards the different results. Low defect state and band offset for the minority carriers in heterojunction solar cells is essential to accomplish high V_{oc} and strong carrier inversion. With the introducing of the passivation film, a decrease in defect state is occurring at the interface. Nevertheless, deliberately tuning of the thickness of the passivation layer is necessary to attain a hard passivation effect. Some points are highlight regarding the SHJs solar cells:

1) SHJ is a huge predict in exceptional because it structurally corresponds to the PV design which allows the bifacial light absorption.
2) Especially thanks to the ideal passivation which created in solar cells, which enables us to lead toward a theoretical limit and also help us to achieve record performance by using a low temperature.
3) A hard and fast control of parameter in the synthesis of practical HIT solar cells. The loss in efficiency can be preferable to the process of variation. Nevertheless, thanks to flat panel industry which their help nanometer deposition

now becomes possible in a good control manner.

4) Substantial innovation in the modeling of solar cells as such passivation, bifacial design and contact topology continues to enhance the cell achievement. It authorizes that the productivity will proceed up to the theoretical limit with the advance device, process plus module innovations.

Aside of device physics, the fundamental challenge is the price of the solar cell. Once the issue of price is handled satisfactorily, the SHJ calls are anticipated to find far-flung acceptance for the prevailing PV technology in the overall world.

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