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A REVIEW ON PERFORMANCE IMPROVEMENT OF SOLAR CRYSTALLINE SILICON PHOTOVOLTAIC CELLS

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ABSTRACT

Energy use has become a crucial concern in the last decades as the rapid increase of energy demand. Renewable energy resources have a positive effect on energy supply security as well as environmental protection. Solar energy is one of the most potential renewable and not significantly vulnerable with the seasonal weather. Solar energy is widely observed as a major renewable energy source, which in future energy systems wills be able to contribute to the security of energy supply. Photovoltaic cell is one of the important options for the solar energy. In this paper, the several current methods to improve crystalline silicon cells conversion efficiency have been presented.

***Keyword*:** Crystalline Silicon Cells.

1. INTRODUCTION

Photovoltaic or solar energy is one of the energy sources in human daily life. It is renewable energy and as an alternative energy source to provide electricity in clean and safe environment (GCEPSU, 2006). Solar energy is abundant and widely used in terrestrial application such as utilities power system, telecommunication, transportation, commercial product and others. The benefits of solar energy cause it widely used in worldwide and become competitive in market of energy sources (Govinda et al, 2010). Photovoltaic expanded when there was energy crisis on oil in 1970s (Nelson, 2003; USMMSRE, 2006). The crisis was due to benefits of photovoltaic on offering clean environmental energy. As results, there were many developments and innovation on solar cells in terms of low cost material, fabrication process, technology process and others. Furthermore, the material used for photovoltaic was abundant and easy to acquire. The important role of solar energy is photovoltaic cell or solar cell which it contributes a lot in energy sources market right now (Green, 1990; Nelson, 2003; Smits, 1976).

Photovoltaic cells are used to convert solar radiation from sunlight into electricity. Nowadays, photovoltaic cells are getting competitive and become active in the photovoltaic market in 2000s (Bruton, 2002; Green, 1990; Ja¨ger-Waldau, 2004; PTM, 2009). Currently, photovoltaic cell can be categorized into several types such as crystalline silicon, thin-film, dye-sensitized and organic cell. These type of cells become competitive each other to achieve the best performance produced by cells manufacturer. Crystalline silicon cells are dominant solar cells in terms of efficiency with >20% leaving distant the second generation of photovoltaic cells; thin-film with <10% efficiency (Miles et al., 2005). Crystalline silicon consist of monocrystalline and multicrystalline (Goerzberger et al, 2003; Miles et al., 2005). Monocrystalline are formed by silicon single crystal while multicrystalline are formed by silicon multiple crystals respectively. Crystalline silicon cell is abundant element in crust of earth, non-toxic material and part of solid-state semiconductor as well as in microelectronic industry. Therefore, many researches about crystalline silicon have been improved and implemented. It also encourages many establishment of solar cell manufacturer in many countries (PTM, 2009). The aim of the research is to study several current methods in improving conversion efficiency of crystalline silicon cells.

2. SOLAR CELLS PERFORMANCE IMPROVEMENT

Crystalline silicon cells conversion efficiency can be improved by considering several criteria such as reflection loss, surface recombination, contact resistance, sheet resistance and others (Green, 2001; Saga, 2010). There are various techniques in term of material or technology to improve cell efficiency. The conventional crystalline solar cells can be improved by modifying cells structure like two bus-bar and three bus-bar cells (Caballero, 2010) and selective emitter (Hilali & Rohatgi, 2004; Rahman, 2012). Selective emitter contributes to high output power because it can reduce surface recombination velocity and enhance minority carrier lifetime. Surface textured method can reduce the reflection loss of cell (Saga, 2010).

A. Two bus-bar and three bus-bar cells

Series resistance of cells is very important in enhancing conversion efficiency (Caballero, 2010) that is shown in Fig. 1. Bus-bar is one the component in solar cells which allows current flows through soldered points attached on it. Thus generated current of solar cell is produced by bus-bar. In industrial solar cell, many manufacturers produce crystalline silicon cells into sub bus-bar; two bus-bar and three bus-bar. Two bus-bar and three bus-bar cells show different performance in electrical properties especially conversion efficiency. This can be simplified into total resistance of two bus-bar in Eq. (1) (Caballero, 2010) as shown below:

$$R_{Series} = \frac{\sum R_{components}}{9n} \qquad (1)$$

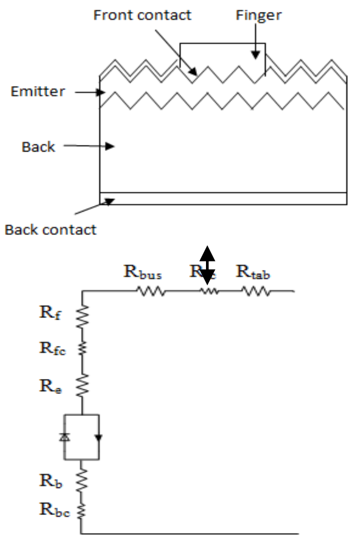

Figure 1: Cross-section and schematic diagram of cells (Caballero, 2010).

While total resistance of three bus-bar in Eq. (2) (Caballero, 2010) as follows:

$$R_{Series}=\frac{\sum R_{components}}{12n} \qquad (2)$$

Therefore, low total resistance can reduce the power loss all at once increase the conversion efficiency of cells. This can observed through series resistance distribution in Fig. 2 and 3. Fig. 4 and 5 shows the solar cell performance between two bus-bar and three bus-bar cell based on specific shadow factor 7.3%. The shadow factor represents the efficiencies for both cells in each point of the optimal finger separation. In this case, the 100 µm of optimal finger width is used while bus-bar width is modified for both cells in order to reach the exact shadow factor.

In Fig. 4, the efficiency shows increasing of two bus-bar cell with ~16.72% efficiency and three bus-bar cell with ~16.83% efficiency at 7.3% of shadow factor. Meanwhile, Fig. 5 defines the bus-bar width by maintained the shadow factor with 7.3%. It shows the width of two bus-bar cell is 2.31mm while three bus-bar cell is 1.76mm.

B. Surface textured

Surface textured is important for cells because it can reduce reflectance loss once photons are absorbed via cells. There are various methods to improve the pyramid textured of solar cells (Chang & Kim, 2010; Xun et al, 2011). However, high efficiency can be achieved by solar cells through surface decoupling technique (Prajapati et al. 2010). This technique is applied to texture wafer on one side while polish to other side. Maximum photons can be captured on wafer front side whereas perfect mirror is represented by wafer rear side to enable reflect the photon to be absorbed into silicon. The process of random pyramid texturing for monocrystalline cells begins with wafer formation through wire saw method. The other alternative to form pyramid texture is by using dielectric layer. Dielectric layer or masking layer is employed at the wafer rear side which can reduce the loss of silicon. This layer is applied between completing

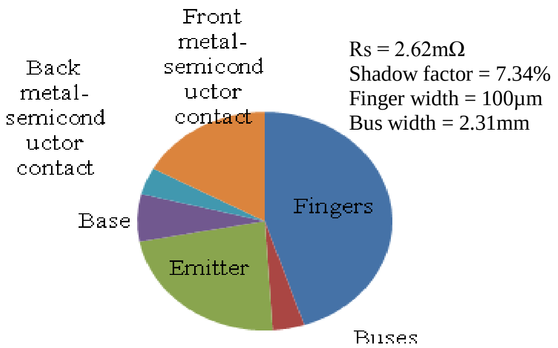

Figure 2: Two bus-bar cell series resistance distribution (Caballero, 2010).

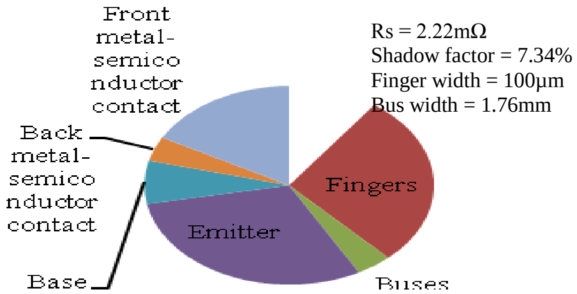

Figure 3: Three bus-bar cell series resistance distribution (Caballero, 2010).

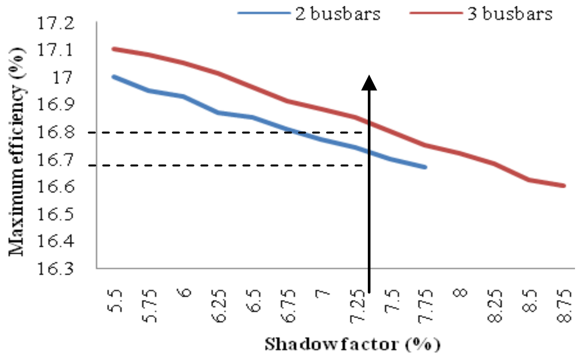

Figure 4: The efficiency comparison of two bus-bar and three bus-bar cells in 7.3% shadow factor (Caballero, 2010).

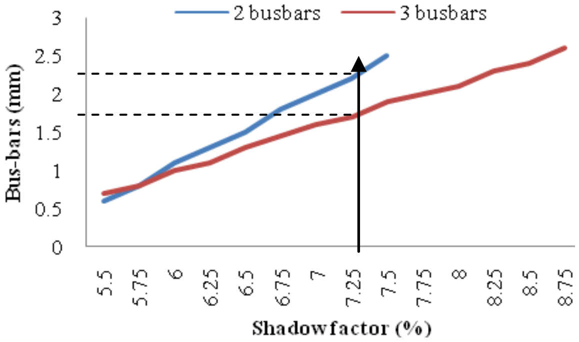

Figure 4: The efficiency comparison of two bus-bar and three bus-bar cells in 7.3% shadow factor (Caballero, 2010).

SDR and texturing process. Plasma texturing or dry etching is a new method to improve pyramid textured. The SDR on rear side is polished through vacuum processing and step of wet etch. The comparison of new method and random pyramid is shown in Fig. 6.

The cell performances result in Table 1 and 2. From Table 1, cells has achieved the best performance when apply new method of pyramid texture
Which achieves 18.4% efficiency, 37.2mA/cm^2 J_{SC}, 640mV V_{OC} and 77% FF.

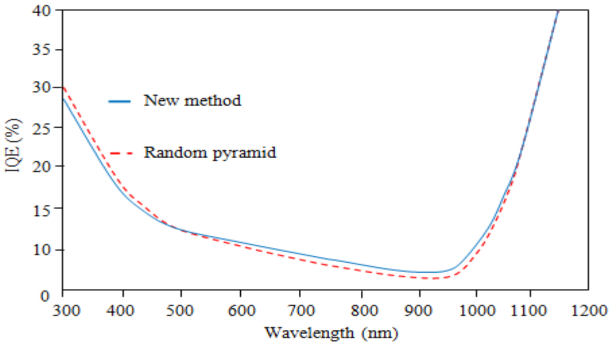

Figure 6: The comparison of reflectance data between new texturing method and random pyramid textured (Prajapati et al., 2010).

C. Selective emitter

The innovation of crystalline silicon solar cell keeps continuing until the new structure of crystalline silicon solar cell is introduced. The new structure of conventional crystalline silicon solar is by inserting selective emitter into cells (Antoniadis et al, 2010; Fellmeth et al., 2011; Hallam et al.; Kray et al., 2010; Sugianto et al., 2010)). Selective emitter is widely used in current solar cells because it can reduce the recombination losses by reducing contact resistance and light doping in the area of n+ emitter. Therefore, it can enhance short circuit current and open circuit voltage of cells. This technology is introduced and implemented in Cougar cell by Innovalight which achieves high performance in conversion efficiency (Antoniadis et al., 2010).

The selective emitter in Cougar cell is formed by using screen-printed technology which it is applied between textured process and emitter formation process. Consequently, the printed area with highly doped is produced. This area achieves 30 to 50 Ohm/sq of sheet resistance. Meanwhile, emitter area has reached 80 to 100 Ohm/sq of sheet resistance. The strength of doping in printed area and in emitter area are independently adjusted. The schematic diagram of Cougar cell is shown in Fig. 7. The IV characteristics are compared between Cougar cell and conventional standard cell. 100 samples of each cell are evaluated and their average values are presented in Table 3. The Table shows that Cougar cell has higher average efficiency 18.9% compared to standard cell 17.95%. Cougar cell is also higher in J_{SC} and V_{OC} than standard cell.

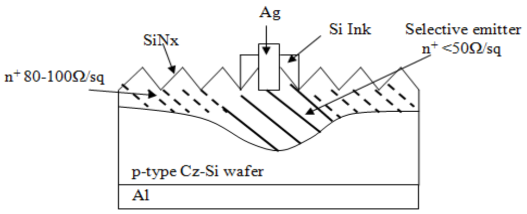

Figure 7: Schematic diagram of Cougar cell by using Silicon Ink from Innovalight (Antoniadis et al., 2010).

Table 1: The performance of best cells (Prajapati et al., 2010).

Type-thickness	Area [cm^2]	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Random Pyramid – 135µm	156	37.0	638	75	17.7
New Texture - 160µm	156	37.2	640	77	18.4

Table 2: The performance of average cells (Prajapati et al., 2010).

Type-thickness (# Cells)	Area [cm^2]	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Random Pyramid – 135µm (4)	156	35.8	640	75	17.2
New Texture - 160µm (15)	156	36.9	639	75	17.7

Table 3: The comparison of I-V parameters average values between Cougar cells and reference cells (Antoniadis et al., 2010).

Cell Structure	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Cougar Average (100 cells)	37.6	637	78.9	18.9
Reference Average (100 cells)	36.5	621	79.2	17.95

D. Perc-type solar cell

Conventional crystalline silicon solar cell structure can be improved by applying passivation or dielectric layer. Passivation layer can be applied either on emitter (front wafer) or on rear of wafer or both (Das et al., 2008; Li et al., 2010). PERC-type cells are tested and constructed by different types of passivation layers to observe cell performance (Ortega et al., 2011; Schmidt et al., 2008; Sun et al., 2008). There are three types of passivation layers tested; 1) Thermal SiO_2, 2) ALD-Al_2O_3, 3) intrinsic a-Si:H PECVD. PERC-type solar cell structure is shown in Fig. 8. Cells are categorized in to three groups where each group consists of different surface passivations; 1) first group with thermal SiO_2, 2) second group with Al_2O_3 layer and 3) third group with combination of Al_2O_3 layer and PECVD-SiO_X layer. Subsequently, these three group of cells under-go the same process following the deposition of dielectric layer and the result shown in Table 4. Meanwhile, internal quantum efficiency IQE for these groups is tested to evaluate the velocity of surface recombination and reflectance of internal rear that are shown in Fig. 9 and Table 5.

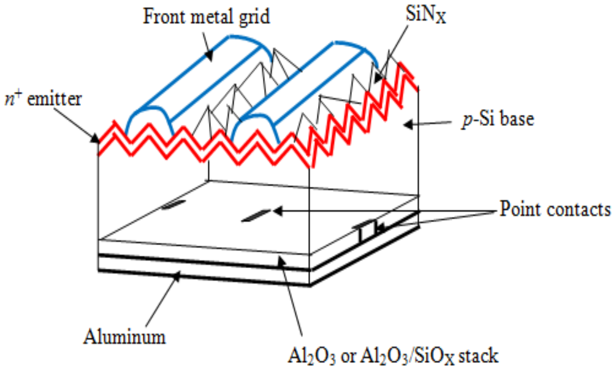

Figure 8: The structure of PERC-type solar cell (Schmidt et al., 2008).

Table 4: Performance of PERC-type solar cell in three types of passivation layers (Schmidt et al., 2008).

Rear side	Cell ID	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Thermal SiO_2 (220nm)	7-1	38.9	656	80.3	20.5
	Average of 4	38.4 ± 0.5	655 ± 1	80.3 ± 1.3	20.2 ± 0.3
ALD-Al_2O_3 (130nm)	3-3	38.7	655	78.9	20.0
	Average of 4	38.6 ± 0.1	656 ± 2	79.4 ± 1.4	20.0 ± 0.4
ALD-Al_2O_3 (30nm) / PECVD-SiO_X (200nm)	2-4	39.0	660	80.1	20.6
	Average of 8	38.6 ± 0.3	657 ± 2	80.4 ± 1.1	20.4 ± 0.4

E. Perl-type solar cell

PERL-type solar is another structure of solar cell besides PERC-type solar cells. PERL-type solar cell is passivated emitter and rear local diffused cells (Kluska & Granek, 2011; Lai et al., 2011; Mack et al., 2010; Upadhyaya et al., 2009). PERL-type solar cells are almost similar with PERC-type cells but PERL-type cells has local diffused on rear side. On this method, PERL-type solar cells are represented by Delta-STAR cells. Delta-STAR cells is constructed and tested to observe the cell performance (Upadhyaya et al., 2009). The cell fabrication process of Delta-STAR cell begins with process of damage etching and chemical cleaning of wafers using Fz and Cz silicon. Similar to PERC-type solar cells, dielectric layer is deposited on both sides of wafer surfaces to form surface passivation that is shown in Fig. 10.

The combination of Al_2O_3 layer and PECVD-SiO_X layer for surface passivation on rear side has obtained the best result with efficiency of 20.6%, V_{OC} of 660mV and J_{SC} of 39mA/cm^2. It is also similar with IQE test which surface passivation layer of Al_2O_3 and PECVD-SiO_X showing the lowest velocity of surface recombination on rear side (70 ± 20 cm/s) among passivation layers. Both thermal SiO_2 layer and Al_2O_3 layer have same surface recombination velocity (90 ± 20 cm/s). The lowest velocity of surface recombination is better to reduce recombination loss on rear surface. The PERL-type solar cells are tested with different types of dielectric layer. Both dielectric layers have the same substrates on different groups of cells; 1) first group with thermal SiO_2, 2) second group with thermal SiO_2 and PECVD SiNx deposition, 3) third group with thermal SiO_2 and Al_2O_3 layer deposition and 4) fourth group with thermal SiO_2, Al_2O_3 layer and PECVD SiNx deposition.

Therefore, result before and after post firing is shown in Fig. 11. The third and fourth groups have rear surface recombination velocity with > 200 cm/s which results to high recombination loss after post firing. It shows the dielectric layer of thermal SiO_2 and PECVD SiN_X is able to produce the low velocity of surface recombination with < 50 cm/s after post firing. Further, another test is analyzed and compared with different base resistivity and area of Delta-STAR cells. It is also compared with PERC-type solar cell which has full area of Al-BSF and the result is summarized in Table 6. It shows that Delta-STAR cell has the highest efficiency of 20.1%. It shows the large area Delta-STAR cell has higher efficiency of 18.5% than the PERC-type cell of 17.4% although the area of large area Delta-STAR cell is lower than the area of PERC-type solar cell.

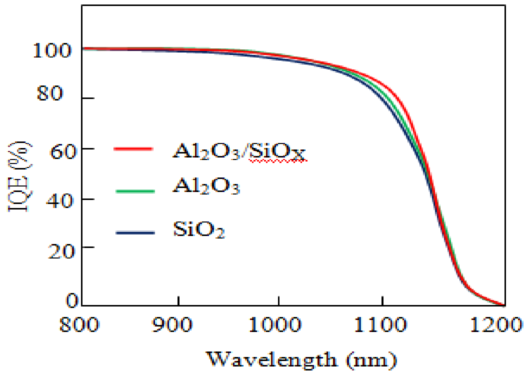

Figure 9: Internal quantum efficiency of PERC-type solar cell in three types of passivation layers (Schmidt et al., 2008).

Table 5: Velocity of rear surface recombination and reflectance of internal rear for PERC-type solar cell in three types of passivation layers (Schmidt et al., 2008).

Rear side	Rear surface recombination velocity Sr [cm/s]	Internal rear reflectance Rr [%]
Thermal SiO_2 (220nm)	90 ± 20	91 ± 1
Al_2O_3 (130nm)	90 ± 20	90 ± 1
Al_2O_3 (30nm) / SiO_X (200nm)	70 ± 20	91 ± 1

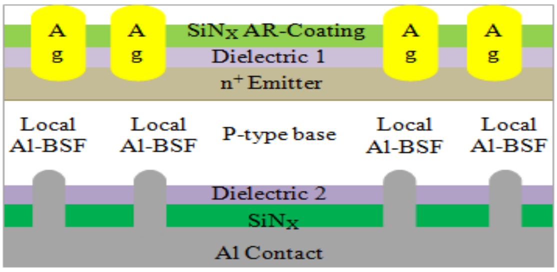

Figure 10: Delta-STAR cell structure schematic (Upadhyaya et al., 2009) .

Meanwhile, the comparison for both cells are tested through the velocity of recombination on front and rear surface as well as internal reflectance of rear by using IQE tester. The summarized result is referred in Table 7 and Fig. 12. It shows the large Delta Cell has lower of 100 000 cm/s FSRV and 125 cm/s BSRV than the PERC-type cell of 150 000 cm/s FSRV and 400 cm/s BSRV. While internal reflectance of rear for the large Delta Cell with 93% is higher than the PERC-type cell with 65%. It is clear that the large Delta Cell has achieved high performance with front and rear dielectric layer as well as LBSF compared to the PERC-type cell with conventional Al-BSF.

F. UV Laser on dielectric stack

The improvement of solar cell also relates to the technology development in solar cell production. Screen printing technology is widely used in cell development. Laser technology is a new technology applied in many solar cells productions. It provides consistency, accurate and productivity in cells processing. There are various types of laser technology which applied in solar cell industry such as laser doping (Hallam et al.; Lee et al., 2010; Sugianto et al., 2010), laser fired contact (Ortega et al., 2011), laser chemical processing (Kluska & Granek, 2011; Kray et al., 2010) and UV laser (Ramanathan et al., 2010). Nanosecond pulse-width of UV laser increases the conversion efficiency. Thus, Delta-STAR cells in high efficiency cells is compared in term of opening dielectric removal process through screen printing technology and laser technology. The structure of Delta-STAR cell is shown in Fig. 13 where UV laser is used to remove the dielectric opening. The cells performances are evaluated through I-V characteristic and IQE measurement and summarized in Table 8.

From Table 8, it proves that cell with base 1.3 Ohm/sq resistivity in screen printing is the highest efficiency with 20.3%. It is followed by cells efficiency by using UV laser for 1 pulse with 20.1 % and 5 pulses with 20%. It is observed that V_{OC} and J_{SC} for three cells are almost equal. The high V_{OC} and J_{SC} are achieved by applying multiple pulses on cell. However, FF becomes lower with multiple pulses. Meanwhile Delta-STAR cell with base 2.3 Ohm/sq resistivity by using screen printing is also compared with previous three cells. It shows the increasing of resistivity results to J_{SC} increases and fill factor decreases. 2.3 Ohm/sq resistivity has similar efficiency with cells of using UV laser for 1 pulse. Fig. 14 shows the IQE response of cells comparison. In Fig.14, it shows the cells with screen printing technology have the better response compared with UV laser. The same response is shown by both cells with UV laser of 1 pulse and 5 pulses although both cells are slightly lower than screen printing. It shows laser technology can achieve high efficiency by replacing screen printing technology without defect to the cells performance.

Table 6: The comparison of Delta STAR cell and PERC-type cell with AL-BSF cells (Upadhyaya et al., 2009).

Cell	Base Ω-cm	Area [cm^2]	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Delta-STAR Small Cell $POCl_3$	2.35	4	39.4	652	78.1	20.1
Delta STAR Large Cell $POCl_3$	1.3	4	38.7	655	77.8	19.7
Delta STAR Large Cell $POCl_3$	1.6	62	36.1	646	79.4	18.5
Al-BSF	1.6	149	35.7	620	78.5	17.4

Table 7: The comparison of Delta STAR cell and PERC-type cell with AL-BSF cells in velocity of front and rear surface recombination (Upadhyaya et al., 2009).

Parameter	18.5% $POCl_3$ Delta Cell	17.4% $POCl_3$ Al-BSF
FSRV (cm/s)	100 000	150 000
BSRV (cm/s)	125	400
R_b	93% (Diffuse)	65% (Diffuse)

Table 8: The data summary from cell measurement (Ramanathan et al., 2010).

Cell	Resistivity Ω-cm	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
Screen printed etch-paste vias	1.3	38.7	657	79.8	20.3
Laser ablated – 1 Pulse	1.3	39.0	652	79.0	20.1
Laser ablated – 1 Pulse	1.3	38.6	653	79.5	20.0
Screen printed paste	2.3	39.4	653	78.1	20.1

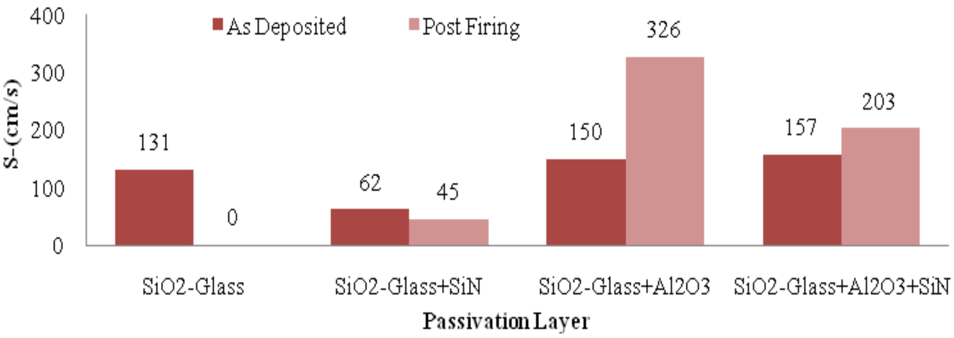

Figure 11: The velocity of surface recombination of PERL-type with different types of dielectric layer before and after post firing (Upadhyaya et al., 2009) .

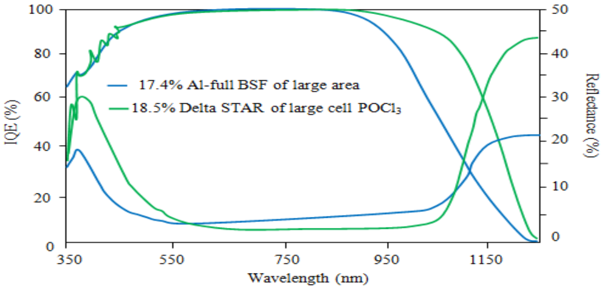

Figure 12: The comparison of IQE measurement and reflectance curves between the best of PERC-type cell and the best Delta-STAR cell (Upadhyaya et al., 2009).

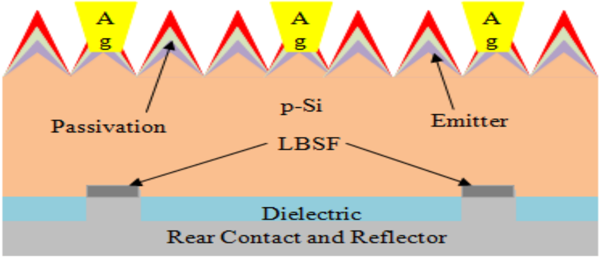

Figure 13: Delta-STAR cell structure schematic (Ramanathan et al., 2010).

G. N-type cell

Most of methods on previous explanation and improvement are implemented by using p-type wafer. However, the n-type wafer can be also implemented to produce high efficiency solar cell. N-type wafer does not have light-induced degradation problem by using Cz technology compared to p-type wafer. Furthermore, tolerance achieved by n-type wafer in metal impurities is higher than p-type wafer. Thus, the n-type wafer minority carrier is higher than p-type wafer which it easy to form junction especially on the back side of wafer. The method to improve high efficiency n-type wafer can be referred to several publications (Bock et al., 2010; Hoex & Brendel, 2010; Das et al., 2011; Gong et al., 2010; Mihailetchi et al., 2008; Woehl et al., 2011). One of the methods used by n-type wafer to improve efficiency is by using back-contact back-junction cells (Woehl et al., 2011). This cell is applied with aluminum-alloyed emitter to reach high conversion efficiency. The schematic of back-contact back-junction cells with aluminum-alloyed emitter is shown in Fig. 15.

Table 9 shows the performance of solar cell. It shows the increasing emitter coverage leads to increase J_{SC} but decrease in V_{OC}, FF and efficiency. Decreased in FF is due to the shunt problem occurred when rear surface overlaps with the peak emitter fraction of cell printed Al finger. It shows the efficiency and FF drop when emitter coverage is 72%. From Table 9, the highest efficiency of 19.7% is achieved by 58% emitter coverage.

Table 9: Solar cell electrical parameter performance in different emitter coverage (Woehl et al., 2011).

Emitter coverage (%)	J_{SC} [mA/cm^2]	V_{OC} [mV]	FF [%]	Eff. [%]
45	37.2	643	79.3	19.0
58	38.8	641	79.3	19.7
72	39.1	638	70.3	17.5

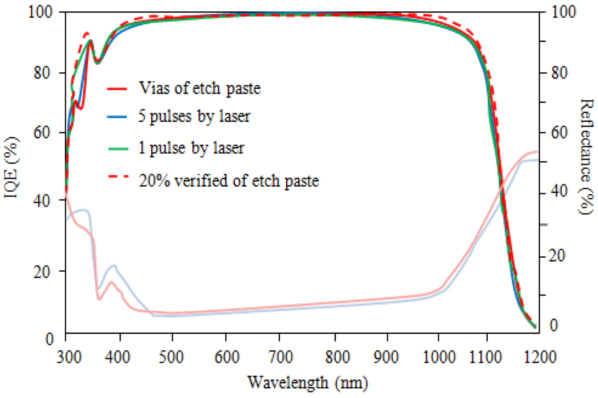

Figure 14: Cells comparison in IQE measurement (Ramanathan et al., 2010).

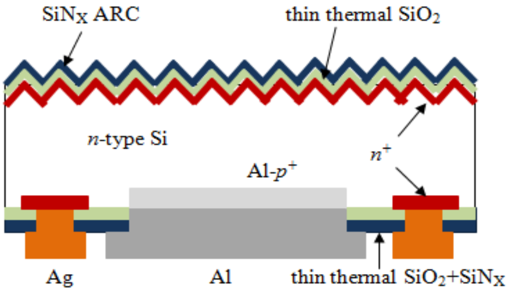

Figure 15: The schematic of back-contact back-junction cells with aluminum-alloyed emitter (Woehl et al., 2011).

3. CONCLUSION

There are several current methods in improving conversion efficiency that has been introduced for crystalline silicon cells. Conventional crystalline solar cells are improved by modifying cells structure like two bus-bar and three bus-bar cells which difference efficiency between them is 0.1%. Therefore, low total resistance can reduce the power loss all at once increase the conversion efficiency of cells. Subsequently, plasma texturing improve pyramid textured by achieving 18.4% of efficiency for the best cell performance. Surface textured is important for cells because it can reduce reflectance loss once photons are absorbed via cells.

The modified cell structure by using selective emitter reaches efficiency in average of a hundred cells with 18.9%. Selective emitter is widely used in current solar cells because it can reduce the recombination losses by reducing contact resistance and light doping in the area of n+ emitter. It is followed by structure cells of PERC-type cell and PERL-type cell with 20.6% and 20.1% respectively for cell efficiency. This is due to passivation layer or dielectric layer applied to the cells in order to improve internal reflectance and surface recombination velocity for front and rear side of silicon wafer.

Laser technology is the popular technology used in cell production and it produces 20.1% of efficiency which it is almost same with screen-printing technology. Most of manufacturers use laser technology because it is easy and can reduce the cost production of cells. All the method mentioned previously is mostly applied to the p-type wafer. However, n-type wafer can also produce high efficiency by using back-contact back-junction cells with 19% of efficiency achievement. Nowadays, many crystalline silicon cells in industry designed in two and three bus-bar. It is evident that the increasing of bus-bar leads to reduce the total resistance of solar cell. Therefore, further work can be suggested and applied another bus-bar which can minimize solar cell total resistance without affecting solar cell performance. The recent development of solar cell is introduced by new design of crystalline silicon cell with metal wrap through concept MWT. MWT concept can be applied to PERC and PERL type of solar cell. It can improve the velocity of surface recombination and full-area aluminum metallization parasitic absorption of solar cells.

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