Research on power loss of solar cell modules

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ABSTRACT
After the encapsulation step, a c-Si solar module's output is usually decreased, in comparison to its cells' power, which is referred to as 'power loss.' This paper focuses on the various factors that can impact power loss of solar modules, such as solar cell classification, encapsulation material, match of solar cells, the encapsulation process used, and so on. The conclusion indicates that power loss in solar modules can be significantly decreased with a resulting increment of a module's output by appropriately optimizing those factors.

Introduction

Solar cells must be connected in series or parallel and encapsulated into modules in order to obtain current, voltage, output power and to prevent them from mechanical or environmental damage. As a general rule, the output power of the encapsulated module (actual power) is less than the summation power of all the solar cells (theoretical power), which is known as 'power loss' and calculated as follows:

power loss = (theoretical power-actual power)/theoretical power. (1)

If the power loss is high and the output power of modules is lower than design value, this poses a major problem for customers. Complaints would have a bad impact on the module company and cause economic loss. Conversely, decreased power loss will cause an increment in the module's output which could increase revenue, lessen the cell efficiency needed for the module encapsulation and reduce the production costs indirectly.

After analysis and discussion of the possible factors that may impact power loss from the aspect of optical loss and electrical loss respectively, this paper shows some elementary conclusions which could provide reference for a module company to improve its product performance. This paper only aims at the study of power loss when modules are encapsulated, excluding the decrease of module output power caused by LID (light induced degradation) etc.

Analysis of power loss

A typical encapsulation scheme [1,2] of the crystalline silicon solar cell is shown in Fig 1. The components, from top to bottom, are tempered glass, sealant, crystalline silicon solar cell, sealant and back sheet.

We classify power loss according to optical loss and electrical loss. The impact factors will be discussed in detail in the following paragraphs.

Figure 1. Structure of laminated module.

Optical loss

In theory, single crystalline silicon solar cells cannot convert all the light that strikes it into electric energy. The spectrum response of normal silicon solar cells ranges from 300nm to 1100nm approximately. As a result, the factors that reduce the light entering the solar cell will cause optical loss, which can be analyzed from the viewpoint of both light transmission and reflection.

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Transmitted from the module surface to the silicon inner, the light will pass through glass and sealant in turn (usually ethylene-vinyl acetate – EVA), both of which have impact on the light absorption. The higher the transmission rates of glass and EVA are, the lower the power loss of modules is. The transmission rate of regular ultra-white tempered glass is approximately 92%. However, the transmission rate of coated glass with anti-reflection film which has been sold on the market can be as high as 96%. Normally, the coated glass can improve the output power of modules by 1%. However, further research on the long-term stability and reliability is needed for this kind of glass.

Fig. 2 illustrates that the transmission rate of 3.2mm-thick tempered glass from different manufacturers changes with wavelength (300nm–1100nm). Sample D is coated glass and the other three are normal tempered glasses. It is clear

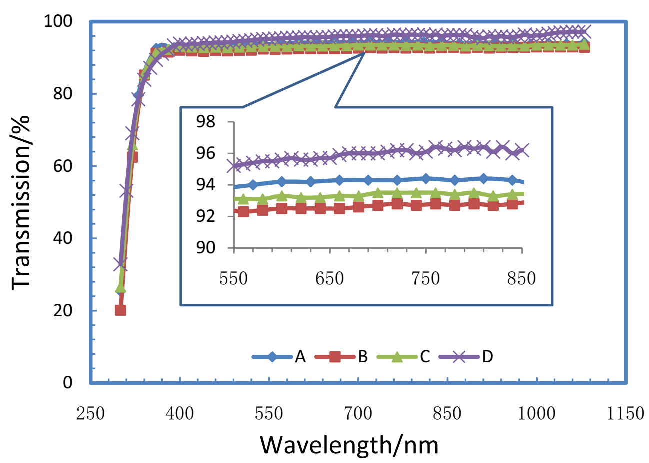

Figure 2. Transmission of glass (thickness 3.2mm). Samples A, B and C are normal tempered glasses from different manufacturers; sample D is coated glass.

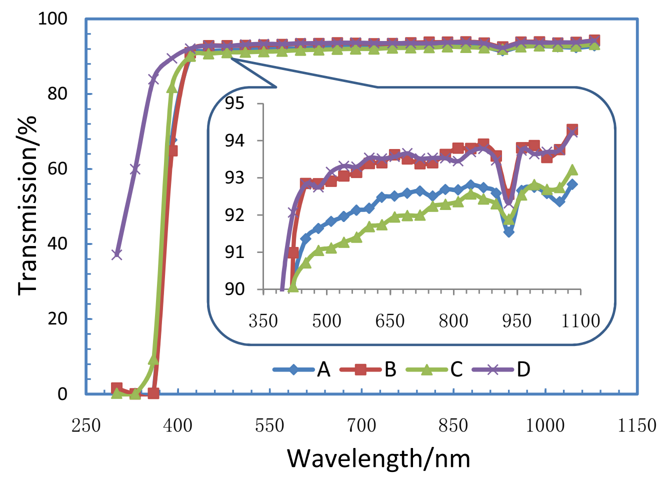

Figure 3. Transmission of EVA (thickness 1.5mm).

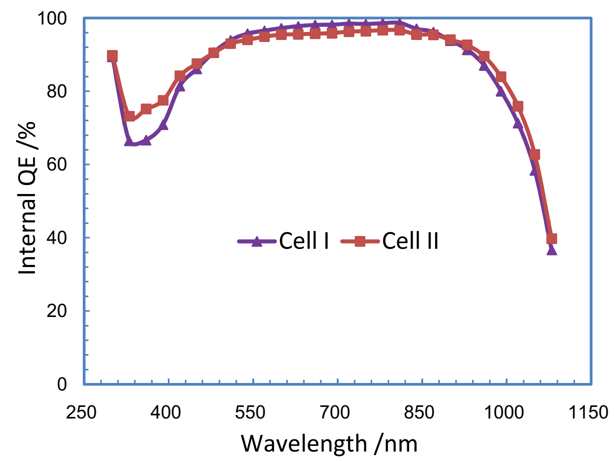

Figure 4. IQE curves of normal cell (Cell I) and high R_{sh} cell (Cell II).

that the transmission rates of glass from different manufacturers show a large variation. The higher the transmission rate, the more light can enter into the solar cell, and the output power of solar cell is proportional to light intensity. Assuming that solar cells and encapsulated material remain unchanged, the output power of modules will increase and power loss will decrease by using tempered glass with high transmission rates.

An anti-UV component can be added into EVA by manufacturers, which will result in the decrease of transmission rates for short wavelengths. Fig. 3 is a diagram demonstrating the transmission rate of EVA (1.5mm thick) produced by different factories. Sample D, the material without UV absorbency shows a transmission rate of 37.1% with 300nm wavelength. The other three EVA with the anti-UV component have no spectral response for light with wavelength shorter than 360nm. However, solar cell manufacturers are starting to use high sheet resistance and close finger processes to increase solar cell conversion efficiency. A solar cell with high sheet resistance (R_{sh}) has a different spectrum response from the conventional p-type solar cell.

Fig. 4 illustrates different IQE curves of a normal cell (Cell I) and high sheet resistance cell (Cell II) with similar efficiency. The IQE of the high sheet resistance cell is higher than that of the normal cell at short wavelength (<450nm). However, on application of the kind of EVA that cannot work at short wavelengths, this short wavelength light cannot be absorbed by the high sheet resistance cell. Consequently, the power loss will be higher than that of normal cells with the same efficiency, illustrating why the selection of EVA should match the cell manufacturing process and balance the transmission rate and anti-UV characteristics, which may reduce the power loss without affecting the module reliability. Furthermore, some companies propose that transparent silica gel with a stable chemical property, anti-UV characteristics and high transmission rate, can be used as a module sealant to prevent problems such as yellowing of sealant which prevents the absorption of short wavelength light by the cell.

An anti-reflection coating of SiN_x is deposited on the solar cell surface with refractive index of 2.1, which is covered by EVA and tempered glass (the total refractive index of 1.48). The thickness of SiN_x, EVA and glass need to be optimized to maximize the module transmission rate, anti-reflection effect as well as the output power.

The module back sheet prevents vapour from entering the module. TPT (Tedlar-PET-Tedlar) film is often used as the back sheet. Fig. 5 shows the reflectivity curve of normal white TPT to EVA contact surface: the reflectivity is as high as about 80% at mid-long wavelength. White TPT film is able to reflect the sunlight which cannot be absorbed by the solar cell. This part of sunlight is reflected to the solar cell from the air-glass interface, thus increasing the utilization of light incident to the solar cells. Compared with black TPT, white TPT could improve the output power by 1%, which can contribute to reducing module power loss.

EVA is used to bind the glass, cell and back sheet. Due to its UV instability, long-

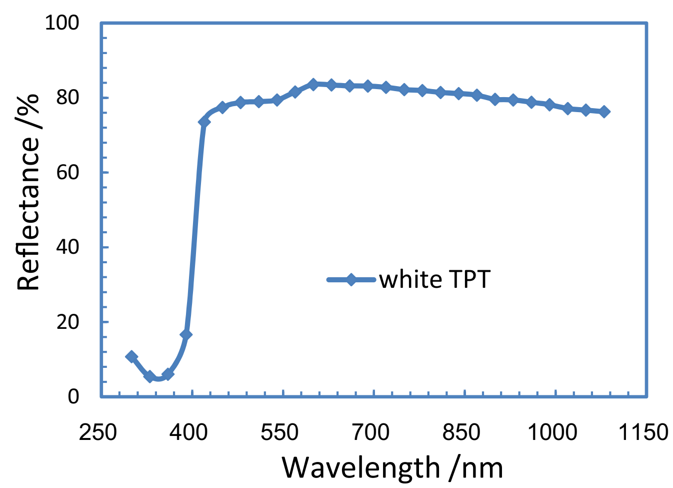

Figure 5. Reflectance of white TPT.

term irradiation by sunlight consisting of 6% UV light may result in its aging, cracking and yellowing. As a consequence, the transmission rate will be decreased, and those parts of the solar cells that are covered by ribbon cannot absorb the sunlight. Therefore, some ribbon companies produce light-reflecting ribbon which has grooves and silver plating on the top surface, which can reflect the light incident on the ribbon into the glass inner surface from some certain angles. The light then can be totally reflected from the glass-air interface to the cell surface. Theoretically, this light absorption is able to increase the module efficiency by approximately 2% [3].

Electrical loss

In practice, solar cells are rarely used individually. They are usually connected in series, parallel, or both, to form modules that satisfy current or voltage demand. Due to the mismatch of solar cells, the actual power output of the connected module is probably lower than the maximum output power of the component cells. When solar cells are connected in series, the total voltage is equal to the summation of the component cells' voltage, whereas the total current is limited by the smallest current of component cell. When solar cells are connected in parallel, the total current is equal to the summation of the component cells' current, and its voltage is the average of all component cells' voltage. The common module is connected by cells in series. If a 'bad' cell with low current is connected into the module, as discussed above, the output current of module is determined by this low current [4]. Consequently, the module output power will decrease and power loss will increase. In order to reduce this kind of power loss resulting from mismatched solar cells in module, solar cells with the same or similar electrical characteristics need to be selected to be connected into the module in series. Hence, a proper classification method is necessary when solar cells are sorted in order to prevent solar cell mismatch.

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Solar cells are connected by ribbon in modules. A solder strip is usually a copper ribbon with Sn plating on the surface. The Sn layer contains Sn/Pb, Sn/Pb/Ag or Sn/Pb/Bi, etc. The resistance of a solder strip is determined by copper ribbon. If the resistance is too high, parts of the module output power could be dissipated on the solder strip which causes electrical power loss. The metal resistance is yielded by multiplying resistivity by metal length divided by metal cross-section area. As the resistivity and length are fixed, the strip resistance can be reduced by increasing the width and thickness of the solder strip. However, the width of a solder strip cannot be increased because if the width of the solder strip becomes wider than the busbar of the solar cell, then the shading area will be enlarged and the solar cell efficiency will be reduced. Therefore, increasing the width of the copper ribbon needs to be considered, but a thicker solder strip can cause cell fragmentation when soldering. Accordingly, solder strips of suitable width and thickness should be chosen to be encapsulated into modules to prevent the module output power from dissipating on the solder strip.

The soldering process has a major impact on module output power. During the soldering process, errors such as cold solder joint and solder skips can occur, causing the contact resistance to go up and the module current to decrease. Improper soldering process can cause electrodes to fall off the wafer, which means that the current cannot be collected completely and the power loss escalates.

Experiment and discussion

Comparison of solar cells with different SiN_x thickness

We chose three groups of single crystalline S125-D165 (diagonal 165mm) silicon solar cells with different SiN_x thickness and efficiencies of 17.25% to be encapsulated into modules (4×9=36pcs of cells in series). During the PECVD process, the SiN_x thickness is adjusted as 70-75, 80-85 and 90-95 (nm) respectively. Each group of solar cells are made into five modules and all the other components remain unchanged. Theoretical module power output is 96.15W; Table 1 illustrates the results.

SiN_x thickness (nm)	Module No (pcs)	Avg. P_{max} (W)	Power loss (%)
70-75	5	95.95	2.05
80-85	5	95.99	1.60
90-95	5	96.00	1.57

Table 1. Power loss of solar cells of varying SiN_x thicknesses.

It is obvious from the collected data that modules with thicker SiN_x have a higher power output and a lower power loss, which can be attributed to optical loss. A possible explanation is that the match of thick SiN_x, EVA and glass is quite beneficial to anti-reflection, hence increasing the module output power.

Comparison of sorting by Eff and I_{ap}

Solar cells are usually sorted by efficiency (Eff). As discussed in earlier, currents of solar cells in series should be as equal as possible, so sorting by I_{ap} should be considered. Single crystalline silicon S156 solar cells with 17.75% efficiency are sorted by Eff and I_{ap} separately and encapsulated into modules (6×10=60 pcs of cells in series). The solar cells are manufactured by two different production lines and the theoretical output power of the resulting module is 254.4W. The average output power of the modules, standard deviation of each group of modules output power and average power loss of each group are calculated.

Table 2 shows that power loss of classification by Eff is 0.39% lower than classification by I_{ap} when the solar cells are produced in the same S156 production lines (line A); there are some differences between power losses of modules encapsulated by S156 solar cells sorted by I_{ap} from different production lines. I_{ap} classification has little impact on power loss, but brings about a smaller standard deviation.

Comparison of different solar cell production lines

Owing to the fact that there is a discernable difference between power losses of solar cells made by different production lines, S125 solar cells produced by two different production lines were selected. Modules (6×12=72pcs in series) were encapsulated with three groups of solar cells with 17.5% efficiency. One group is made by line A, the second group comprises line B and the last group is made by solar cells mixed from lines A and B. The theoretical output power of module is 195.08W. The standard deviation of each group of modules' output

Sorting type	Production line	No. (pcs)	Avg. P_{max}(W)	Deviation	Power loss (%)
Eff	line A	59	245.29	1.65	3.58
I_{ap}	line A	50	244.30	1.48	3.97
I_{ap}	line B	58	246.26	1.36	2.20

Table 2. Power loss of Eff & I_{ap} classification.

Production line	No. (pcs)	Avg. P_{max} (W)	Deviation	Power loss (%)
line A	13	189.40	0.45	2.93
line B	13	189.03	0.64	3.12
mixed line	14	188.64	1.04	3.32

Table 3. Power loss of modules comprising cells from different production lines.

Current (mA)	No. (pcs)	Avg. power (W)	Deviation	Power loss (%)
I_1	8	187.49	1.45	2.47
I_2	8	187.45	1.46	2.49
I_3	8	186.42	1.51	3.03
Ref	15	187.22	2.05	2.64

Table 4. Current subdivision.

power and the average power loss of each group are calculated.

From the results in Table 3, modules encapsulated by solar cells from the same production lines were seen to have a lower power loss and better output power uniformity than solar cells mixed from different production lines. The standard deviation of line A is smaller than that of line B, and line A also has a lower power loss than line B. These differences are most likely caused by the differences in equipment and calibration.

Subdivision of solar cells' current

Solar cells with 17.25% efficiency are divided into three groups by current, I_1:5.274~5.299mA, I_2:5.249~5.274mA, I_3:5.224~5.249mA. The current of the reference group is not subdivided. The theoretical output power of these four groups of modules is 192.3W.

Table 4 illustrates that the subdivision of current has little impact on power loss. However, the output power of the module changes gradually by current subdivision. Group I_1 has the largest output power while I_3 has the smallest. After encapsulation, the reference group (current non-subdivision) of modules was found to have the smallest standard deviation.

Impact of different ribbons on power loss

Ribbons with different specifications were used to form three groups of modules. The thickness by width are: 0.15 × 1.6, 0.18 × 1.6, 0.20 × 1.6 (mm). Referring to the previous discussion it is clear that the resistances of three groups are reducing. Solar cells with 17.50% efficiency are encapsulated into modules (6×10=60 pcs in series), the theoretical output power of which is 250.8W.

The data in Table 5 shows that the output power of the module increases with thicker ribbon, while the power loss is also lower. However, thick ribbon can lead to high cost and high fragment rates when soldered manually. Nevertheless, if the automated soldering line is used, any concerns about this high fragment rate by manual soldering is eliminated; thick ribbons will cause an incremental module output power and detrimental power loss. In the long run, thick ribbons are beneficial to controlling the quality of modules, increasing yield of modules and reducing the production cost.

Conclusion

The power loss of modules can be divided into optical loss and electrical loss. The former contains losses resulting from limitation in the transmission rate of glass and sealant and extra power by the absorbtion of light reflected by ribbons and the back sheet. The latter contains losses caused by mismatch, ribbon resistance and current loss by bad soldering.

Solar cell classifications by efficiency or I_{ap} have little impact on the module output power. Similarly, subdivision does not have much impact on power loss, although it does contribute to the output power uniformity. The power loss of modules encapsulated by solar cells produced by the same production line is smaller than that of solar cells taken from different production lines.

The improved anti-reflection effect that results from optimization of matching the SiN_x film, EVA and glass is beneficial to increasing module output power.

Assuming there is no influence on the long-term stability and reliability, accessories should be chosen to increase the output power and decrease the power loss, such as glass/sealant with high transmission rate and soldered ribbons with high conductivity.

Ribbon type (mm x mm)	No. (pcs)	Breakage (%)	Avg. power (W)	Power loss (%)
0.15 × 1.6	30	1.7	242.12	3.46
0.18 × 1.6	30	2.7	242.78	3.20
0.20 × 1.6	22	4.5	243.49	2.91

Table 5. Module encapsulation with different ribbons.

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