

Photovoltaic Module

Field

The present invention relates to a photovoltaic module.

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Background

A study of the levelized cost of electricity (LCOE) of photovoltaics (PVs) in Singapore reveals that the grid parity of solar electricity can be achieved either with aggressive price reduction, or with innovative technology strategy (i.e. see
10 chart 100 of FIG. 1). For example, focusing on the technology innovation, the study suggests that increased module sustainability, decreased module degradation rate per annum, as well as increased module energy yield are some key points that will further reduce the LCOE of PV in Singapore. Bifacial technology is a fairly promising concept to achieve high module energy yield.
15 Bifacial solar cell absorbs light from its front and rear surfaces to generate electricity. Under bifacial illumination, more current/power will be generated per unit area of the solar module. Furthermore, due to the reduced bow in bifacial cells, less cell breakage occurs during the modularization process. The latest International Technology Roadmap for Photovoltaic (ITRPV 2016) has
20 forecasted that bifacial technology will increase its global market share from approximately 5% in year 2016 to about 30% in the next decade.

Bifacial solar cells can be integrated into different module structures: (1) glass/glass bifacial PV modules; (2) glass/transparent backsheet bifacial PV
25 modules; and (3) glass/backsheet monofacial PV modules. Bifacial PV modules with a transparent rear surface collect additional sunlight at the rear surface of the modules, by capturing light reflected from the surface beneath the modules, as well as from the surroundings (albedo). As a result, bifacial PV modules are able to generate additional energy in outdoor conditions compared to the
30 standard monofacial PV modules. In addition, the glass/glass structure offers higher durability and reliability, compared to the glass/backsheet structure.

An in-depth characterization of the optical losses in a glass/glass bifacial PV module was performed in a related literature. With reference to diagram 200 of
35 FIG. 2, the optical losses include reflection losses at various interfaces (1: air-

glass, 2: glass-encapsulant, 3: encapsulant-cell), absorption losses (4: glass, 5: encapsulant), and transmittance losses (6: cell transmittance, 7: cell-gap transmittance). The reflection and absorption losses are common for all types of PV modules. The transmittance losses are additional optical losses in a bifacial PV module. Transmittance measurement on a glass/cell structure shows that a significant amount of near infrared (IR) light (i.e. at 950-1200nm wavelengths) passes through the bifacial cell (i.e. curve "BB" in chart 300 of FIG. 3). When the bifacial cell is encapsulated with a glass on the rear surface (in a glass/cell/glass structure), the cell transmittance losses are observed to increase (i.e. curve "AA" in chart 300 of FIG. 3). Compared to the glass/cell structure, about 0.45% of current loss is observed for the glass/cell/glass structure. In contrast, when the bifacial cell is encapsulated with a standard backsheet on the rear surface (in a glass/cell/backsheet structure), most of the light transmitted through the bifacial cell is reflected back and absorbed by rear surface of the bifacial cell, leading to a current gain of about 0.9%, versus the glass/cell structure. Thus, under standard test conditions (STC), a bifacial cell that uses the glass/glass structure incurs about 1.3% optical loss compared to one which uses the glass/backsheet structure, due to the bifacial cell transmittance losses.

Moreover, the light incident on the cell-gap area of a glass/glass module passes straight through the module, unlike a glass/backsheet module where the incident light is scattered at various angles due to the scattering and reflection properties of the backsheet. Light that is scattered at an angle greater than the total internal reflection angle of front glass-air interface (i.e. approximately 42°) will be totally internally reflected at the front glass-air interface and redirected back to the front side of the bifacial solar cells for absorption. As a result, a glass/glass PV module with bifacial cells shows 2-3% cell-gap loss compared to a standard glass/backsheet PV module as measured under STC.

One objective of the present invention is therefore to address at least one of the problems of the prior art and/or to provide a choice/solution that is useful in the art.

Summary

According to a 1st aspect, there is provided a photovoltaic module comprising: first and second substrates configured to be optically transparent; and a plurality of bifacial photovoltaic cells configured to generate electricity from light received
5 through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another. To enable further electricity generation, the second substrate has a plurality of first portions having a first reflective coating to reflect light passing through the spacings to the photovoltaic cells, and at least a plurality of
10 second portions having a second reflective coating to reflect light of near-infrared wavelengths to the photovoltaic cells. The plurality of first portions are arranged to correspond to the spacings.

Advantageously, by having the plurality of first and second reflective coatings at
15 the second substrate, the photovoltaic module is able to convert/minimise transmittance losses in standard bifacial modules into additional optical gains instead to enable the photovoltaic module attain a higher power.

Preferably, the first reflective coating may include a coating with a mixture of
20 titanium dioxide, silicon dioxide, and zinc oxide.

Preferably, the first and second substrates may be glass panels or transparent photovoltaic backsheets.

25 Preferably, the second reflective coating may include an infrared reflective coating which is optically transparent.

Preferably, the plurality of second portions are arranged to substantially correspond to the photovoltaic cells.
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Alternatively, the plurality of second portions may also be collectively arranged to include an entire surface at one face of the second substrate.

Preferably, the first reflective coating may include at least one layer of the first
35 reflective coating.

Preferably, the second reflective coating may include at least one layer of the second reflective coating.

5 Preferably, the spacings may include a mixture of cell gaps arranged to have a width of about 3 mm, and string gaps arranged to have a width of about 5 mm.

Preferably, the photovoltaic cells may include being arranged to be encapsulated with an encapsulant.

10 Preferably, the near-infrared wavelengths may include wavelengths between 950 nm to 1200 nm.

According to a 2nd aspect, there is provided a method of manufacturing a photovoltaic module having first and second substrates configured to be optically
15 transparent and a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another. The method comprises: (i) providing the first and second substrates; (ii) providing electrical connections between the
20 photovoltaic cells to electrically couple the photovoltaic cells together; and (iii) encapsulating the photovoltaic cells with the first and second substrate using an encapsulant to obtain the photovoltaic module, the second substrate arranged in opposition to the first substrate. To enable further electricity generation, the second substrate has a plurality of first portions having a first reflective coating
25 to reflect light passing through the spacings to the photovoltaic cells, and at least a plurality of second portions having a second reflective coating to reflect light of near-infrared wavelengths to the photovoltaic cells. The plurality of first portions are arranged to correspond to the spacings.

30 According to a 3rd aspect, there is provided a photovoltaic module comprising: first and second substrates configured to be optically transparent; and a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced
35 from one another. To enable further electricity generation, the second substrate

has a plurality of portions having a reflective coating to reflect light passing through the spacings to the photovoltaic cells; and the plurality of portions are arranged to correspond to the spacings.

- 5 Preferably, the reflective coating may include a coating with a mixture of titanium dioxide, silicon dioxide, and zinc oxide.

According to a 4th aspect, there is provided a photovoltaic module comprising: first and second substrates configured to be optically transparent; and a plurality
10 of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another. To enable further electricity generation, the second substrate has at least a plurality of portions having a reflective coating to reflect light of
15 near-infrared wavelengths to the photovoltaic cells.

Preferably, the reflective coating may include an infrared reflective coating which is optically transparent.

20 According to a 5th aspect, there is provided a photovoltaic module comprising: first and second substrates configured to be optically transparent; and a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced
25 from one another. To enable further electricity generation, the second substrate has at least a plurality of portions configured with a layer having textured surfaces to both reflect light passing through the spacings and reflect light of near-infrared wavelengths to the photovoltaic cells.

30 Preferably, the layer having the textured surfaces may include a photovoltaic backsheet arranged to be optically transparent.

According to a 6th aspect, there is provided a photovoltaic module comprising: first and second substrates configured to be optically transparent; and a plurality
35 of bifacial photovoltaic cells configured to generate electricity from light received

through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another. To enable further electricity generation, the second substrate has a plurality of first portions having a reflective coating to reflect light passing
5 through the spacings to the photovoltaic cells, and at least a plurality of second portions configured with a layer having textured surfaces to reflect light of near-infrared wavelengths to the photovoltaic cells. The plurality of first portions are arranged to correspond to the spacings.

10 Preferably, the reflective coating may include a coating with a mixture of titanium dioxide, silicon dioxide, and zinc oxide.

Preferably, the layer having the textured surfaces may include a textured photovoltaic backsheet arranged to be optically transparent.

15 It should be apparent that features relating to one aspect of the invention may also be applicable to the other aspects of the invention.

These and other aspects of the invention will be apparent from and elucidated
20 with reference to the embodiments described hereinafter.

Brief Description of the Drawings

Embodiments of the invention are disclosed hereinafter with reference to the accompanying drawings, in which:

25 FIG. 1 is a chart of levelized cost of electricity (LCOE) study of PVs in Singapore;

FIG. 2 is a diagram depicting optical losses in a glass/glass bifacial PV module;

FIG. 3 is a chart of measured transmittance for various PV module structures in the long-wavelength region;

30 FIG. 4a shows schematics of a proposed photovoltaic (PV) module, according to an embodiment;

FIG. 4b is a plan view of rear substrate of the PV module of FIG. 4a, in which the rear substrate has different portions applied with IR reflective coating or white reflective coating;

FIGs. 4c and 4d are respective diagrams schematically showing reflection of transmitted light using the IR reflective coating, and light scattering effect on a cell-gap area (using the white reflective coating);

FIG. 5 is a flow diagram of a method of manufacturing the PV module of FIG. 4a;

5 FIG. 6 is a chart of measured reflectance curves of various types of IR reflective coatings;

FIG. 7 is a chart of measured EQE of a reference PV module, and a PV module with IR coating-A and a PV module with IR coating-B;

10 FIG. 8a is a chart of optical gain contributed by various types of IR reflective coatings, and FIG. 8b is a table showing IV-measurement of the reference PV module and the PV module with the IR coating-A;

FIG. 9 is a chart of measured EQE of a reference PV module and a PV module configured with a textured transparent backsheet for 950-1200nm;

15 FIG. 10 is a chart of measured reflectance curves of standard backsheet and various types of white reflective coatings;

FIG. 11 shows an EQE line-scan on the cell-gap area (white reflective coating) of a glass/glass mini-module;

FIG. 12 is a plot of normalized J_{sc} as a function of the distance of illumination point from cell edge;

20 FIG. 13 is a chart of EQE-calculated current gain for varying cell-gap in a full-size cell and in a half-cut cell bifacial PV module with white reflective coating;

FIG. 14 is a chart of EQE-calculated and IV-measured current gain for varying cell-gap and string-gap in a half-cut cell bifacial PV module with white reflective coating;

25 FIG. 15 shows a chart of optical gain of optimized half-cut cell bifacial PV modules compared to a reference/baseline PV module (i.e. a standard glass/glass bifacial PV module without any coating applied);

FIGs. 16a and 16b respectively shows front and rear views of a prototype of the PV module of FIG. 4a, which is formed from half-cut PV cells;

30 FIG. 16c shows a section of the prototype of FIG. 16a;

FIGs. 16d and 16e respectively are a schematic view and a photograph of the rear substrate of the prototype applied with the white reflective coating;

FIG. 17a is a schematic of the prototype of FIG. 16a;

35 FIGs. 17b and 17c respectively present electrical and mechanical parametric characteristics of the prototype of FIG. 16a; and

FIG. 17d shows an IV performance curve of the prototype of FIG. 16a.

Detailed Description of Preferred Embodiments

1. Introduction

5 With reference to FIGs. 4a and 4b, there is disclosed a photovoltaic (PV) module/panel 400 (also known as a bifacial module), according to an embodiment. For illustration purposes, FIG. 4a shows only a portion of the complete PV module 400 (and is also not drawn to scale for any of the features as depicted), but is not to be construed as limiting in any manner. Broadly, the
10 PV module 400 comprises first and second substrates 402, 404 configured to be optically transparent; and a plurality of bifacial photovoltaic (PV) cells 406 configured to generate electricity from light received through the first and second substrates 402, 404, the PV cells 406 arranged intermediate the first and second substrates 402, 404, and are configured to be spaced from one another. The PV
15 cells 406 may be encapsulated in an encapsulant 407. It is to be appreciated that the spacings include a mixture of cell gaps and string gaps. To enable further/additional electricity generation, the second substrate 404 has a plurality of first portions having a first reflective coating 408 to reflect light passing through the spacings to the PV cells 406, and at least a plurality of second
20 portions having a second reflective coating 410 to reflect light of near-infrared wavelengths to the PV cells 406.

The plurality of first portions are arranged to correspond to the spacings, so that the albedo may still enter from the rear substrate 404 of the PV module 400 and
25 be absorbed by the PV cells 406. More than one layer of the first reflective coating 408 may be applied on the first portions, depending on optimisation requirements. For example, a thickness of the first reflective coating 408 may be 30 μm . In turn, the second reflective coating 410 are applied on the second portions, which are areas of the rear substrate 404 not occupied by the first
30 portions; specifically the second portions substantially correspond to areas underneath the PV cells 406. Also, more than one layer of the second reflective coating 410 may be applied on the second portions, depending on optimisation requirements too. The second substrate 404 has first and second faces (lying in the horizontal plane), in which the first face is immediately adjacent to the
35 (encapsulated) PV cells 406, and the second face is in opposition to the first

face. So, the second reflective coating 410 is applicable to the first or second face (but in this instance, the second reflective coating 410 is printed on the second face, as depicted in FIG. 4a), while the first reflective coating 408 is applied to the first face. It is to be appreciated that the first and second
5 substrates 402, 404 are respectively disposed at the front and rear of the PV module 400. So the first and second substrates 402, 404 may also be called front and rear substrates respectively thereafter. Then, the front and rear substrates 402, 404 can be glass substrates or suitable transparent backsheets, but for purpose of this embodiment, glass substrates are assumed to be used for
10 the PV module 400. The first reflective coating 408 may be a white reflective coating (e.g. formed from a coating with a mixture of titanium dioxide, silicon dioxide, and zinc oxide), whereas the second reflective coating 410 may be an infrared (IR) reflective coating. For ease of discussions below, the first and second reflective coatings 408, 410 are thus respectively assumed to be the
15 white reflective coating and the IR reflective coating.

To clarify, light of near-infrared wavelengths to be operatively reflected by the IR reflective coating 410 originates as such: typically, PV cells arranged in a PV module absorb and convert light into electricity. However, the PV cells are
20 generally not sufficiently sensitive to light of near-infrared wavelengths (i.e. about 950-1200nm). This means that part of the near infrared light penetrates the PV cells without being absorbed. For a typical PV module configured with a white reflective backsheet as back cover, the unabsorbed near infrared light first passes through the bifacial PV cells and is then reflected by the white reflective
25 backsheet back to the PV cells for further absorption. But for a bifacial module with a transparent back cover, the unabsorbed near infrared light however escape the bifacial module via the transparent back cover, without being redirected back into the bifacial module. Hence, the purpose of the IR reflective coating 410 arranged on the rear substrate 404 is to enable collection of the light
30 of near-infrared wavelengths back to the PV cells 406 for improving power of the PV module 400. It is also highlighted that the IR reflective coating 410 is configured to only reflect light of near-infrared wavelengths, while still permitting light to enter the PV module 400 via the rear substrate 404 (since the IR reflective coating 410 is optically transparent), and so consequently albedo from
35 the ground/surrounding is able to enter from the rear substrate 404 to the

photovoltaic cells 406 for power generation. Hence, this preserves the advantage of configured the PV module 400 to use the bifacial PV cells 406.

FIGs. 4c and 4d respectively show reflection of light using the IR reflective coating 410, and light scattering effect on a cell-gap area (using the white reflective coating 408).

FIG. 5 depicts a method 500 of manufacturing the PV module 400. Broadly, the method 500 comprises: (i) providing the front and rear substrates 402, 404 at step 502; (ii) providing electrical connections between the PV cells 406 to electrically couple the PV cells 406 together at step 504; and (iii) encapsulating the PV cells 406 with the front and rear substrates 402, 404 using an encapsulant to obtain the PV module 400 at step 506. The rear substrate is 404 arranged in opposition to the front substrate 402. It is to be appreciated that the definition of "encapsulating" carried out at step 506 also includes bonding the front and rear substrates 402, 404 to the PV cells 406.

It is also to be clarified that the white reflective coating 408 and IR reflective coating 410 are coated on the rear substrate 404 first by printing/coating the IR reflective coating 410 on an entire area of the first/second face of the rear substrate 404 (which thus also covers the second portions), or only on the second portions. Next, the white reflective coating 408 is then printed on the first portions (on the first face) of the rear substrate 404. For good order, the above two printing steps are optional to the method 500 of FIG. 5.

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Next, motivations and details for using the IR reflective coating 410 and white reflective coating 408 are set out in the sections below.

2. Experimental Approach

2.1 Reducing bifacial cell transmittance loss by using IR reflective coatings

As afore discussed, a glass/glass bifacial module suffers cell transmittance loss at near-infrared wavelengths (i.e. 950-1200nm). One way to reduce the cell transmittance loss is by using the IR reflective coating 410. The reflective coating 410 reflects the transmitted light back to the rear side of the PV cells 406 for absorption, resulting in a higher module current. To demonstrate the

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feasibility of this approach, several glass/glass bifacial mini-modules 450 are fabricated and the IR reflective coating 410 is applied on the rear glass of the mini-modules 450 (see FIG. 4c). Two types of IR reflective coating 410, IR coating-A and IR coating-B, are investigated. To characterize performance gain of the mini-modules 450 due to the different coatings, external quantum efficiency (EQE) measurements are performed on the mini-modules 450 (i.e. a reference module and modules with the IR reflective coating 410). Short-circuit current density (J_{sc}) of the mini-modules 450 is calculated using Eq. 1:

$$J_{sc} = q \int EQE(\lambda) \cdot \phi_{AM1.5G}(\lambda) d\lambda \quad (1)$$

where q is the charge constant, EQE is the external quantum efficiency of the mini-module 450, and $\phi_{AM1.5G}$ is the photon flux of the standard solar spectrum AM1.5G. Using Eq. 2, the optical gain due to the coatings can be determined:

$$Optical\ gain = \frac{J_{sc,mod,IR} - J_{sc,mod,ref}}{J_{sc,mod,ref}} \quad (2)$$

Alternatively, the optical gain due to the different coatings can be quantified using EQE, bifacial cell transmittance and reflectance measurement results. A portion of the transmitted IR light is reflected by the coatings and subsequently absorbed by the rear side of a PV cell 452 of the mini-module 450. The current gain due to this additional light absorption on the module rear side is quantified in Eq. 3 as:

$$Optical\ gain = \frac{\Delta J_{sc}}{J_{sc,mod,front}} = \frac{q \int EQE_{mod,rear}(\lambda) \cdot T_{mod}(\lambda) \cdot R_{IR-coating}(\lambda) \cdot \phi_{AM1.5G}(\lambda) d\lambda}{q \int EQE_{mod,front}(\lambda) \cdot \phi_{AM1.5G}(\lambda) d\lambda} \quad (3)$$

where $EQE_{mod,rear}$ is the rear side external quantum efficiency of module, T_{mod} is the bifacial cell transmittance in glass/glass module, $R_{IR-coating}$ is the reflectance of the IR-reflective coatings, and $EQE_{mod,front}$ is the external quantum efficiency of the mini-module 450 measured only for front side illumination. To substantiate the measurement results obtained using optical characterization techniques, IV-measurements on the reference module and on modules with the

IR reflective coating 410 are performed using a h.a.l.m. IV tester (with class A+A+A+ sun simulator).

2.2 *Reducing bifacial cell transmittance loss by using textured module rear cover*

Another proposed approach to reduce the bifacial cell transmittance loss is by texturing the rear cover (either a glass panel or a transparent backsheet) of the bifacial modules, in which texturing of the rear cover helps to reflect and redirect the light incident on the rear cover back to the PV cell 452 for absorption. The concept is demonstrated on a glass/transparent backsheet mini-module. The surface of the backsheet is manually textured using sandpapers. To quantify the optical gain from textured backsheet, EQE measurements are subsequently performed on a reference module (with a standard transparent backsheet) and on a prototype module (not shown) of the PV module 400 (having a textured transparent backsheet). The current gain due to the backsheet texturing is quantified using Eqs. 1 and 2.

2.3 *Reducing cell-gap loss in glass/glass modules by using white reflective coatings*

To reduce cell-gap loss of the glass/glass bifacial modules 450, the white reflective coating 408 is used on the rear glass (see FIG. 4d). To maintain the module bifacial performance, the white reflective coating 408 is applied selectively only at portions of the rear glass that correspond to the cell-gap regions. Due to the scattering properties of the white reflective coating 408, a significant amount of incident light is reflected and redirected back to the PV cell 452. Three types of the white reflective coating 408 are investigated. The optical properties of the white reflective coating 408 are first characterized by performing UV-VIS (reflectance) measurements. Next, to quantify the light scattering effect of the white reflective coating 408, an EQE line-scan is performed on mini-module using a spot area illumination (see FIG. 11). The measurements on the cell-gap area are spaced at an interval of 0.5 mm. Subsequently, the J_{sc} of the mini-module 450 is calculated for each illumination point using Eq. 1 and normalized with respect to the J_{sc} measured on module active area. Integration of the normalized J_{sc} for the cell-gap range provides the

current gain contributed by the associated white reflective coating 408 for the corresponding cell-gap.

3. **Results and Discussion**

5 3.1 *Reducing bifacial cell transmittance loss by using IR reflective coatings*

FIG. 6 is a chart 600 depicting the measured reflectance of various types of the IR reflective coating 410. It is found that the IR reflective coating 410 tend to reflects about 75-80% of IR light. FIG. 7 is a chart 700 of the EQE of the reference module (i.e. configured without the IR-reflective coating 410), a
10 module with IR coating-A, and a module with IR coating-B. The EQE of the modules with the IR reflective coating 410 is higher than the EQE of the reference module in the near-infrared wavelengths region (950-1200nm). This indicates that a portion of the transmitted IR light has been recovered by the PV cell 452 through the reflection process occurring at the coating surface. FIG. 8a
15 is a chart 800 of the optical gain calculated using Eqs. 2 and 3, i.e. EQE- and reflectance-calculated optical gain. The reflectance-calculated current gain for IR coating-A is 0.9% and for IR coating-B is 1.07%. The EQE-calculated current gain for IR coating-A is 0.8% and for IR coating-B is 1.01%. Assuming an IR reflective coating that exhibits 100% reflectance in the 950-1200nm wavelengths
20 region, the maximum achievable current gain is thus 1.4% for the given bifacial cell transmittance.

Comparing the optimization potential, cost, market availability and etc. of both coatings, IR coating-A is thus determined to be more viable for PV application.
25 Hence, IV-measurements are performed on the reference module and on the module with IR coating-A to validate the results obtained from the optical characterization of the coating.

From table 850 of FIG. 8b, it can be seen that IR coating-A yields about 0.8%
30 gain in module short-circuit current I_{sc} , as compared to the reference module. This result is in agreement with the EQE measurement results, which similarly show a current gain of 0.8% for IR coating-A.

35 3.2 *Reducing bifacial cell transmittance loss by using textured module rear cover*

As discussed in *section 2.2*, textured module rear cover is a potential approach to reduce the bifacial cell transmittance loss in a bifacial PV module. Results in a chart 900 of FIG. 9 reveal that the associated module with textured backsheet has slightly higher EQE in the near-infrared wavelengths region (950-1200nm), compared to the reference module with a standard transparent backsheet. Using the EQE measurements, the module with textured backsheet has about 0.3% gain in module short-circuit current density. This result indicates that the textured backsheet reduces the bifacial cell transmittance loss. Further optimization of the backsheet texture is necessary to achieve a higher current gain. A reliability study is to be performed to further investigate the potential of this approach as a solution to reduce the transmittance loss in bifacial modules.

3.3 *Reducing cell-gap loss by using white reflective coatings*

FIG. 10 is a chart 1000 presenting the reflectance of various types of white reflective coatings 408 and standard backsheet. It is found that the reflectance of the white reflective coating-3 is highest amongst the various coatings and is similar to the reflectance of a standard backsheet. Thus, the white reflective coating-3 is selected for further performance investigation using EQE measurements and line-scan – see FIG. 11. FIG. 12 shows a plot 1200 of the normalised J_{sc} as a function of the distance of the illumination point from the cell edge of the mini-modules for two different module structures, i.e. glass/backsheet and glass/glass (with the white reflective coating-3).

Using the normalized J_{sc} results, the current gain for a particular cell-gap is calculated. FIG. 13 is a chart 1300 showing the current gain calculated for modules with full-size cell and half-cut cell design. In both cases, as the cell-gap increases, the current gain increases. For the same cell-gap, modules with half-cut cell design have higher current gain than modules with full-size cell design. This observation indicates that the backscattering effect of the white reflective coating 408 is more profound in a half-cut cell module than in a full-size cell module. To validate the EQE measurement results, half-cut cell mini-modules (having 9 photovoltaic cells 406) are fabricated with various cell-gap and string-gap combinations and their IV-characteristics are measured. The results for different cell-gaps are presented in a chart 1400 in FIG. 14. For a half-cut cell module with a cell-gap of 3mm and a string-gap of 5mm, a current

gain of about 3% is obtainable using the white reflective coating 408. Incorporating the IR reflective coating 410 and the white reflective coating-3 into the half-cut cell module with 3mm cell-gap and 5mm string-gap, the optimized glass/glass (half-cut cell) bifacial module has about 4% more optical gain,
5 compared to a standard glass/glass bifacial module without any coating applied (see FIG. 15).

FIGs. 16a and 16b respectively shows front and rear views of a prototype 1600 of the proposed PV module 400, which in this instance is formed from half-cut
10 bifacial PV cells. FIG. 16c shows a portion of the prototype 1600 of FIG. 16a, whereas FIGs. 16d and 16e respectively depict a schematic view and a photograph of the rear substrate of the prototype 1600 applied with only the white reflective coating 408 due to experimental reasons, and hence is in no way to be construed as deviating from the proposed PV module 400. It is to be
15 appreciated that respective areas on the rear substrate 404 (that correspond to the spacings) applied with the white reflective coating 408 may extend with an overlap of 2mm in each direction to ensure substantial coverage of the spacings by the white reflective coating 408. That means, the plurality of first portions are configured to be slightly wider than the spacings themselves.

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FIG. 17a shows schematics of the prototype 1600, but it is highlighted that the indicated dimensions are merely for example, and not to be construed as limiting. FIGs. 17b and 17c respectively are tables 1700, 1710 of electrical and mechanical parametric characteristics of the prototype 1600, and FIG. 17d is a
25 plot 1720 of an IV performance curve of the prototype 1600 (which is configured to be capable of generating around 360.7 W of electrical power), as measured from the front side of the prototype 1600.

Also, the prototype 1600 is characterized by the following device properties:

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- Uses high-efficiency n-type mono-Si cells.
- Has extremely low resistive loss with Multi-busbar (6-busbar cell) and Half-cut cell technologies.
- Arranged as a high power module with 72-photovoltaic cells connected in series.

- Arranged with a 2mm ultra-thin heat-strengthened front glass (AR coated) and rear glass to keep module weight low.
- Arranged with selective white ceramic coating on rear glass to increase module power and energy yield in outdoor conditions.
- 5 • Glass/glass module construction for superior durability and lower power degradation.
- Uses PID-resistant polyolefin encapsulant for encapsulating the photovoltaic cells.
- Able to generate 10-30% higher energy yield per year compared with
- 10 monofacial modules (due to usage of albedo radiation from surroundings).
- Arranged with three separate smaller junction boxes to minimize back-surface shading.

4. Summary

15 The proposed PV module 400 (of FIG. 4a) utilizes advanced light management technology to selectively coat different portions of the rear substrate 404 with the IR reflective coating 410 and white reflective coating 408 in order to enable further electricity generation. Practically speaking, this enables the PV module 400 to enjoy improved front side performance while maintaining the bifaciality

20 advantage. Accordingly, it is envisaged that by adopting the design of the disclosed PV module 400, PV module manufacturers are able to enjoy the premium selling price advantage of bifacial modules (due to higher STC power), whereas end-users of the photovoltaic module 400 are able to obtain higher energy yield versus using standard bifacial modules, which beneficially reduces

25 overall cost of PV electricity generation.

To summarise, the foregoing discussions disclose two demonstrated approaches to enhance the optical performance of glass/glass bifacial PV modules under standard test conditions (STC). Specifically, the IR reflective coating 410 is

30 applied on the rear substrate 404 to reduce the bifacial cell transmittance which occurs at wavelengths of 950-1200nm. Both IR coating-A and IR coating-B reflect about 75-80% transmitted IR light back to the photovoltaic cells 406, which yields a current gain of about 0.8-1.0%. The optical performance of the glass/glass bifacial module 450 is further enhanced using the white reflective

35 coating 408 selectively in the cell-gap area of the module 450. A current gain of

about 3% is achieved for the cell-gap of 3mm and string-gap of 5mm. Combining both solutions (i.e. the IR reflective coating 410 and white reflective coating 408), which are adopted in the PV module 400, about 4% current enhancement is obtained. So, the PV module 400 is able to achieve a better front side performance and a higher energy yield in outdoor conditions, compared to standard bifacial PV modules. It is also to be appreciated that glass/glass module structure is preferred over standard glass/backsheet structure for bifacial solar cells, since the glass/glass module structure enables albedo collection from rear side of the module.

Accordingly, the disclosed PV module 400 substantiates the advantage of glass/glass bifacial PV modules by demonstrating viable concepts to reduce the optical loss caused by the glass/glass design under STC. This sequentially reduces the $\$/W_p$ of the glass/glass module structure. Furthermore, by texturing the rear cover of the module, it is also demonstrated that the bifacial cell transmittance loss can be reduced. Compared to the reference module with a standard transparent backsheet (i.e. a smooth surface), the prototype module with a manually textured transparent backsheet achieves a current gain of about 0.3% (i.e. the textured transparent backsheet is configured to reflect both light passing through the spacings arranged between the the PV cells 406, and light of near-infrared wavelengths passing directly through the PV cells 406, by means of textured surfaces). With further optimization of the texture, higher current gain is expected. It is to be appreciated that the study focuses only on improving the STC performance of the bifacial PV modules. It is envisaged that future work may investigate impact of the proposed approaches on the module bifacial performance. There are also plans to investigate the actual performance of the optimized module under outdoor conditions, as well as to further optimize the coatings. Nevertheless, it is believed that the results of the present study are useful and valuable to module manufacturers and researchers.

Applications-wise, the proposed PV module 400 solves some of the major hindrances for PV module manufacturers to mass-adopt bifacial module technology, and so it is envisaged that the PV module manufacturers would be keen to start manufacture bifacial double-glass modules due to increase in the front-side performance, based on reference design of the PV module 400.

Besides bifacial PV modules, the concept of applying the IR reflective coating 410 and white reflective coating 408 at the rear substrate 404 is also usable on double-glass PV modules (including both monofacial and bifacial modules).

5 While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary, and not restrictive; the invention is not limited to the disclosed embodiments. Other variations to the disclosed embodiments can be understood and affected by those skilled in the art in practising the claimed
10 invention.

For example, the concept of applying the IR reflective coating 410 and white reflective coating 408 to the rear substrate 404 is generally applicable to any PV module having any number of bifacial PV cells 406, and/or having front and rear
15 substrates 402, 404 formed of different materials (other than those afore disclosed). In addition, the proposed PV module 400 may alternatively just have either the IR reflective coating 410 or the white reflective coating 408 at (either first/second face of) the rear substrate 404; it is thus not necessary for the PV module 400 to be configured with both the IR reflective coating 410 and white
20 reflective coating 408, as depicted in FIG. 4a. Also, in a variant embodiment, the PV module 400 may be configured with only the textured transparent backsheet at the first/second face of the rear substrate 404, i.e. both the IR reflective coating 410 and white reflective coating 408 are not needed in this instance. Yet alternatively, the second reflective coating 410 (as depicted in
25 FIG. 4a) may also be replaceable with a layer having textured surfaces (e.g. a textured transparent backsheet) to reflect the light of near-infrared wavelengths to the PV cells 406. Needless to say, the layer with textured surfaces may be applied either only to the second portions, or instead an entire area of the first/second face of the rear substrate 404, depending on needs of an intended
30 application.

Claims

1. A photovoltaic module comprising:
first and second substrates configured to be optically transparent; and
5 a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another,
wherein the second substrate has a plurality of first portions having a first
10 reflective coating to reflect light passing through the spacings to the photovoltaic cells, and at least a plurality of second portions having an infrared radiation (IR) reflective coating to specifically reflect light of near-infrared wavelengths to the photovoltaic cells; and
wherein the plurality of first portions are arranged to correspond to the
15 spacings.
2. The photovoltaic module of claim 1, wherein the first reflective coating includes a coating with a mixture of titanium dioxide, silicon dioxide, and zinc oxide.
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3. The photovoltaic module of any preceding claim, wherein the first and second substrates are glass panels or transparent photovoltaic backsheets.
4. The photovoltaic module of any preceding claim, wherein the IR reflective
25 coating is optically transparent.
5. The photovoltaic module of any preceding claim, wherein the plurality of second portions are arranged to substantially correspond to the photovoltaic cells.
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6. The photovoltaic module of claim 1, wherein the plurality of second portions are collectively arranged to include an entire surface at one face of the second substrate.

7. The photovoltaic module of any preceding claim, wherein the first reflective coating includes at least one layer.

8. The photovoltaic module of any preceding claim, wherein the IR reflective
5 coating includes at least one layer.

9. The photovoltaic module of any preceding claim, wherein the spacings include a mixture of cell gaps arranged to have a width of about 3 mm, and string gaps arranged to have a width of about 5 mm.

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10. The photovoltaic module of any preceding claim, further comprising an encapsulant arranged to encapsulate the photovoltaic cells.

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11. The photovoltaic module of any preceding claim, wherein the near-infrared wavelengths include wavelengths between 950 nm to 1200 nm.

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12. A method of manufacturing a photovoltaic module having first and second substrates configured to be optically transparent and a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another, the method comprises:

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(i) providing the first and second substrates;
(ii) providing electrical connections between the photovoltaic cells to electrically couple the photovoltaic cells together; and
(iii) encapsulating the photovoltaic cells with the first and second substrates using an encapsulant to obtain the photovoltaic module, the second substrate arranged in opposition to the first substrate,

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wherein the second substrate has a plurality of first portions having a first reflective coating to reflect light passing through the spacings to the photovoltaic cells, and at least a plurality of second portions having a infrared radiation (IR) reflective coating to specifically reflect light of near-infrared wavelengths to the photovoltaic cells; and

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wherein the plurality of first portions are arranged to correspond to the spacings.

13. A photovoltaic module comprising:

first and second substrates configured to be optically transparent; and

5 a plurality of bifacial photovoltaic cells configured to generate electricity from light received through the first and second substrates, the photovoltaic cells arranged intermediate the first and second substrates, and are configured to be spaced from one another,

10 wherein the second substrate has at least a plurality of portions having an infrared radiation (IR) reflective coating to specifically reflect light of near-infrared wavelengths to the photovoltaic cells.

14. The photovoltaic module of claim 13, wherein the IR reflective coating is optically transparent.

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