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Design of 4-terminal solar modules combining thin-film wide-bandgap top cells and c-Si bottom cells

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Abstract

Optical simulations of 4-terminal hybrid tandem modules combining high-efficiency crystalline silicon (c-Si) cells with three different thin-film top cells respectively are presented. We considered three types of thin film PV cells: 1. Enlarged-bandgap oxygenated amorphous silicon (a-SiO:H) cells, 2. Wide-bandgap chalcopyrite ($CuGaSe_2$) cells, and 3. Perovskite ($CH_3NH_3PbI_3$) cells. A methodology for evaluating the efficiency gain of the 4-terminal hybrid tandem module is proposed and used to show how the efficiency of an interdigitated back contact (IBC) c-Si module with an efficiency of about 19.5% can significantly be increased through this 4-terminal tandem concept. In our model we also included the change in electrical output parameters by the color-filtering effect of the top cells.

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Keywords: solar module; 4-terminal; tandem; simulation

1. Introduction

For single-junction crystalline silicon (c-Si) solar cells, the previous efficiency record of 25% has been established in 1998 [1]. This record stood for 15 years until last year, when Panasonic announced their back-contacted HIT® cell that reached efficiency of 25.6% [2]. The difficulty in improving the c-Si cell efficiency inevitably limits the module efficiency (current maximum about 22%). The practical limit for single junction c-Si

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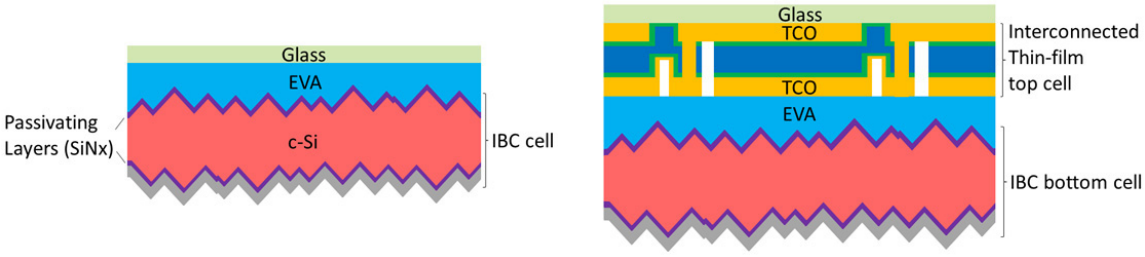
modules is generally thought to be 24-25%. To surpass the practical efficiency limits of single-junction c-Si modules, 4-terminal hybrid tandem modules consisting of wide-bandgap thin-film cells and high-efficiency c-Si bottom cells have been suggested [3]. Compared to the common 2-terminal structure, the 4-terminal hybrid tandem structure has several advantages: no need of current or lattice matching, simple mechanical stacking, more freedom for choosing the top and bottom cells, and most of all the possibility to use monolithic series connection for the thin-film top cell.

In this contribution, a 4-terminal hybrid tandem module structure combing thin-film top cells and c-Si bottom cells is proposed. On the basis of a single-junction IBC module structure (Fig. 1(a)), a thin-film solar cell can be deposited and interconnected on the inner side of the module cover glass as shown in Fig. 1(b), implying a minor change of the single-junction IBC module structure. In the simulation and optical design, an IBC solar cell processed at ECN is adopted as the bottom cell. The design of three types of thin-film solar cells as the top cell has been studied, 1. enlarged-bandgap oxygenated amorphous silicon (a-SiO:H) cells, 2. Wide-bandgap chalcopyrite ($CuGaSe_2$) cells, and 3. perovskite ($CH_3NH_3PbI_3$) cells, and the potential efficiency gain is evaluated.



(a) (b)

Fig. 1. Schematic layer stacks of (a) a single-junction IBC module and (b) a 4-terminal hybrid tandem module combining an interconnected thin-film top cell and a bottom IBC cell.

2. Optical simulation

The optical simulations are carried out with Advanced Semiconductor Analysis (ASA) software developed at Delft University of Technology [4, 5]. Both wave and geometrical optics are included. Layer geometry of solar modules and optical properties of each material are used as input. To evaluate the optical effectiveness of a certain module structure, the weighted fractional absorbance ($\bar{A}$) of a layer in the solar module is defined by the equation:

$$\bar{A}(\%) = \frac{\int_{1200}^{300} A(\lambda)\phi(\lambda)d\lambda}{\int_{1200}^{300} \phi(\lambda)d\lambda}, \quad (1)$$

where $A(\lambda)$ is the net absorbance of a layer in the solar module taking into account the transmission and reflection of all other layers in the stack, $\phi(\lambda)$ is the photon flux of the AM1.5 solar spectrum and thereby $\bar{A}$ indicates the fraction of the absorbed photons in the AM1.5 solar spectrum. Note that only the wavelength range of 300 nm to 1200 nm is considered since the photon flux at wavelengths shorter than 300 nm is negligible and c-Si has no absorption at wavelengths longer than 1200 nm. The photocurrent density corresponding to absorption (either photocurrent gain or loss) in a specific layer (J_a) can be estimated from the equation:

$$J_a(\mathrm{mA/cm^2}) = q\int_{1200}^{300} A(\lambda)\phi(\lambda)d\lambda = \bar{A} \times 46.46\ \mathrm{mA/cm^2}. \quad (2)$$

Note that 46.46 mA/cm^2 is the ideal maximum J in case that all the photons at wavelengths ranging from 300 nm to 1200 nm of the AM1.5 solar spectrum are absorbed to generate electron and hole pairs, which are then collected without any losses. The weighted fractional reflectance ($\bar{R}$) and the corresponding photocurrent density loss J_R can be calculated similarly by using the specific reflectance $R(\lambda)$. To evaluate the current output of solar modules, we assume that the J_a of the active layer (the intrinsic a-SiO:H layer for a-SiO:H cells, the $CuGaSe_2$ layer for $CuGaSe_2$ cells, the $CH_3NH_3PbI_3$ layer for perovskite cells and the c-Si "layer" for c-Si cells) is equal to the short-circuit current (J_{sc}) of the solar cell. Since reflection losses of the module and parasitic absorption losses from layers other than the active layer are taken into account, this assumption is acceptable for estimating J_{sc} if the thickness of the active layer is smaller than the diffusion length of minority carriers [5, 6] in c-Si and the collection length in the thin film cells (determined by combined drift and diffusion mechanisms). The optical performance of a hybrid tandem module can be evaluated by the sum (J_{sc_sum}) of the J_{sc} from the top cell (J_{sc_t}) and the J_{sc} from the bottom cell (J_{sc_b}).

3. Results and discussion

3.1 Optical design of hybrid tandem modules

Initial calculation shows that, compared to the IBC module structure in Fig. 1(a), implementation of thin-film solar cells onto the inner side of flat module glass (Fig. 1(b)) drastically increases reflection and parasitic absorption losses of modules, making this hybrid tandem concept difficult to result in a gain in efficiency. The reasons for the increase of reflection losses are that a thin-film solar cell introduces multiple interfaces with contrasting refractive indices of its layers. The thin layers at a scale of ~ 100 nanometers cause strong light interference effects. For example, as shown in Fig. 2(a), the reflection of a hybrid tandem module with a-SiO:H top cells leads to a reflection loss of about 9 mA/cm^2, which accounts for 19% of the photons at wavelengths ranging from 300 nm to 1200 nm in the AM1.5 solar spectrum. The intrinsic a-SiO:H layer thickness influences the J by interference effects. To reduce the reflection loss, a random pyramid-like micrometer-scale texture, replicated from an etched c-Si wafer, can be introduced onto the module glass. In practice it can be realized by imprint lithography [7]. The pyramid-like texture on the module glass can effectively decrease the reflection loss from 9 mA/cm^2 to 4 mA/cm^2, and further down to 2.5 mA/cm^2 with double-sided texture as shown in Fig. 2(a). Furthermore, the influence of light interference caused by the thin layer is almost eliminated. The schematic layer stack of the hybrid tandem module with the textured module glass is illustrated in Fig. 2(b) and also used in the latter simulation. The major parasitic absorption in the hybrid tandem module originates from the Transparent Conductive Oxide (TCO) layers since in 4-terminal tandem concepts, TCO has to be used as both the front and rear electrodes of the top cell. The free carrier absorption in the near-infrared severely reduces the number of photons that are left for absorption by the c-Si bottom cell. In order to reduce this parasitic absorption of TCO, the hydrogen doped indium oxide (IO:H) material with low free-carrier density and very high mobility, which was published recently [8], is a very promising candidate as a TCO for semitransparent thin film cells and has therefore been used as the TCO of the hybrid tandem module in the modelling for this paper. Layer stacks of different solar cells and layer thicknesses used as input of the simulation are listed in Table 1.

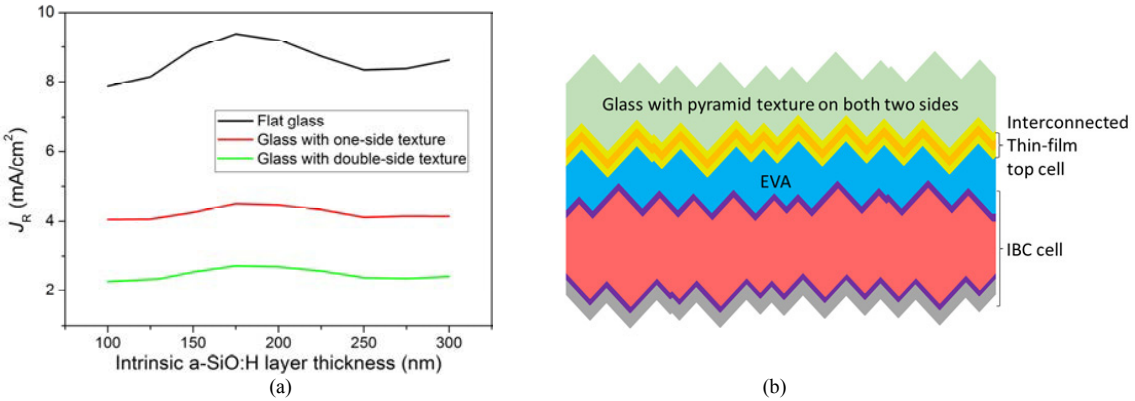


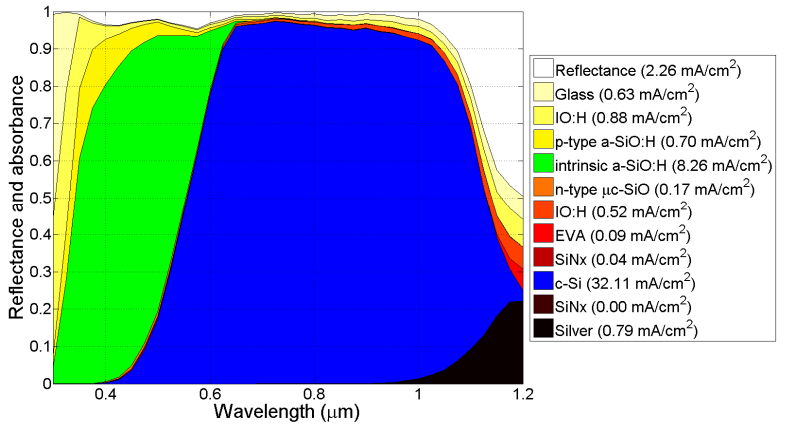
Fig. 2. (a) Reflection losses in terms of the current density for hybrid tandem modules with different glass morphology and different intrinsic a-SiO:H layer thickness and (b) schematic layer stacks of hybrid tandem modules with textured module glass.

Table 1. Layer stack and thickness of different thin-film top cells and c-Si bottom cells used as input of the simulation. Note that there is also 100-µm thick EVA between the top and bottom cells.

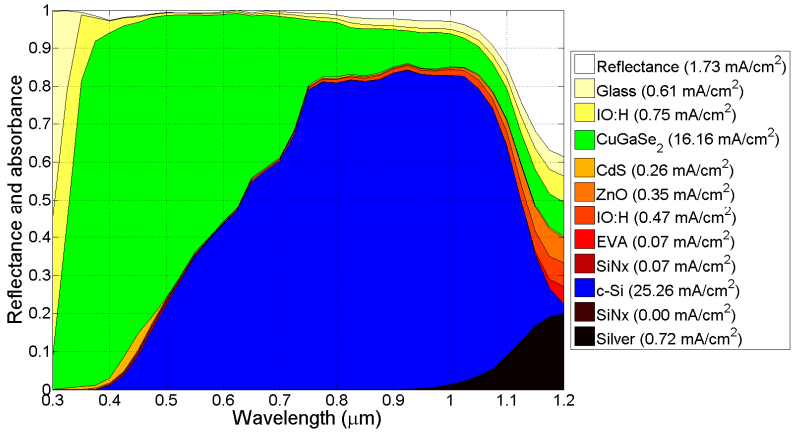
a-SiO:H top cell		**$CuGaSe_2$ top cell**		**Perovskite top cell**		**c-Si bottom cell**	
Layer	Thickness (µm)	Layer	Thickness (µm)	Layer	Thickness (µm)	Layer	Thickness (µm)
Glass	2000	Glass	2000	Glass	2000	SiN_x	0.08
IO:H	0.1	IO:H	0.1	IO:H	0.1	c-Si	160
p-type a-SiO:H	0.01	CGS	0.1	Compact TiO_2	0.1	SiN_x	0.08
Intrinsic a-SiO:H	0.1	CdS	0.055	$CH_3NH_3PbI_3$	0.1	Silver	20
n-type µc-SiO:H	0.02	ZnO	0.09	Spiro-OMeTAD	0.3		
IO:H	0.1	IO:H	0.1	IO:H	0.1		

The module reflectance and the absorbance of each layer are simulated for three kind of top cells as shown in Fig. 3. The optical simulation in Fig. 3(a) shows that the J_{sc_sum} of the hybrid tandem module with an a-SiO:H top cell can reach 40.37 mA/cm^2. Although the IO:H and doped layers lead to parasitic absorption losses of 1.4 mA/cm^2 and 0.87 mA/cm^2 respectively, the losses from the encapsulating layer of EVA and the passivating layer of SiN_x become negligible in the presence of the top cell. For the hybrid tandem module with a $CuGaSe_2$ top cell as shown in Fig. 3(b), the J_{sc_sum} is 41.42 mA/cm^2. The IO:H leads to a parasitic absorption loss of 1.22 mA/cm^2. Since the light comes from the glass side of the $CuGaSe_2$ solar cell, CdS and ZnO are located at the rear, leading to a small parasitic loss of 0.82 mA/cm^2. Note that there is significant absorption at wavelengths longer than 730 nm, although the optical bandgap of $CuGaSe_2$ is about 1.7 eV. If this is parasitic sub-gap absorption not leading to free carriers, the J_{sc_sum} of the hybrid tandem cell with a $CuGaSe_2$ top cell will be 3.92 mA/cm^2 lower. Further clarity on this sub-gap absorption is needed. Optical simulation of the hybrid tandem module with a perovskite top cell (Fig. 3(c)) shows a high J_{sc_sum} of 41.41 mA/cm^2. The reason for the high J_{sc_sum} is that refractive indices of the layers in the perovskite cell do not diverge much, leading to a smaller reflection loss. Furthermore, the compact TiO_2 and Spiro-OMeTAD only cause a small parasitic absorption loss of 0.33 mA/cm^2.

To summarize this section, the hybrid tandem module with the designed texture and high-quality TCO is capable of generating a J_{sc_sum} of over 40 mA/cm^2, which is similar to the J_{sc} of a high-performance IBC module [1]. This means that no significant optical losses are caused by adding the thin-film cells onto the inner side of the IBC module glass. It should be noted that although the J_{sc_sum} is not considerably higher than the J_{sc} of an IBC cell, this tandem structure represents a large efficiency gain because the charge carriers due to the high energy photons are extracted at higher operating voltage.



(a)



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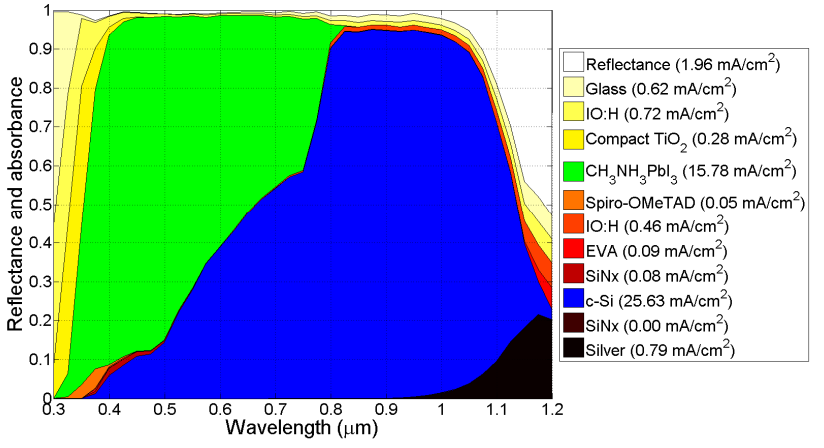


(c)

Fig. 3. Simulated reflectance and absorbance spectra of 4-terminal hybrid tandem modules with (a) a-SiO:H top cells (J_{sc_t}=8.26 mA/cm^2 and J_{sc_b}=32.11 mA/cm^2), (b) $CuGaSe_2$ top cells (J_{sc_t}=16.16 mA/cm^2 and J_{sc_b}=25.26 mA/cm^2) and (c) Perovskite top cells (J_{sc_t}=15.78 mA/cm^2 and J_{sc_b}=25.63 mA/cm^2). The J calculated from the reflectance and absorbance is listed in the legend.

3.2 Efficiency estimation of hybrid tandem modules

To evaluate the efficiency gain of a hybrid tandem module, V_{oc} and FF changes of the c-Si bottom cell at lower light intensity or smaller J_{sc} have to be taken into account. With the two-diode equation and the orthogonal distance regression (ODR) fitting method, the J-V curve of our IBC cell processed at ECN can be fitted to obtain the device parameters such as saturation current, ideality factors, series and shunt resistance. Therefore, the J-V curve at other light intensities and concomitant J_{sc} can be deduced. Fig. 4(a) shows how V_{oc} and FF of our IBC cell change with J_{sc}. The product $V_{oc}\cdot FF$ of the IBC cell is plotted as a function of the J_{sc} as shown in Fig. 4(b) and the curve is mathematically fitted with a polynomial function so that the IBC cell efficiency can be expressed by J_{sc} a single variable. Therefore, the efficiency of a hybrid tandem module (η) with the given IBC bottom cell can be expressed by the equation:

$$\eta(\%) = \eta_t + \eta_b = V_{oc\_t}\cdot FF_t \cdot J_{sc\_t} + J_{sc\_b}\cdot(0.412 + 0.00362\cdot J_{sc\_b} - 0.0000429\cdot {J_{sc\_b}}^2), \qquad (3)$$

where η_t and η_b are respectively the efficiency of the top and bottom cells, V_{oc_t} and FF_t are the open-circuit voltage and the fill factor of the top cell. Eq. 3 leads to Fig. 5, assuming that J_{sc_sum} is equal to a constant of 40 mA/cm^2. The dots in Fig. 5 indicate the possible efficiency of a hybrid tandem module that could be achieved by introducing different thin-film solar cells onto the IBC module cover glass, starting from an IBC module with an efficiency of about 19.5%. The J_{sc_t} for different thin-film solar cells are taken from Fig. 3 and the product $V_{oc}\cdot FF$ of three different top cells is taken from the literature [9, 10, 11]. This offers the possibility to make a hybrid tandem module with an efficiency of over 24%. For a-SiO:H and $CuGaSe_2$ top cells, the absolute efficiency gain will be about 2.5% and 3% respectively. The use of a perovskite top cell can lead to a significant absolute efficiency gain of over 5%.

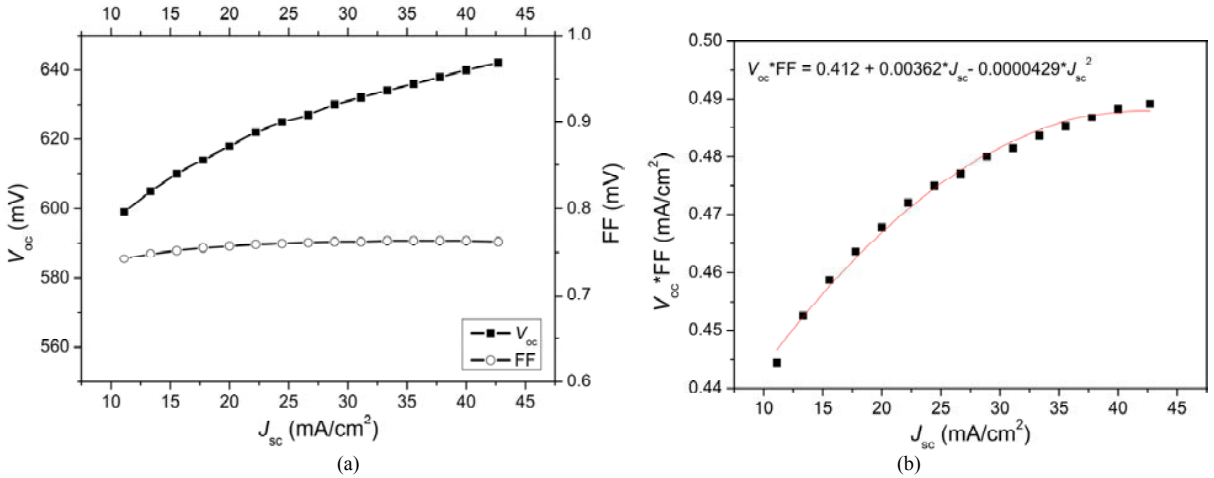
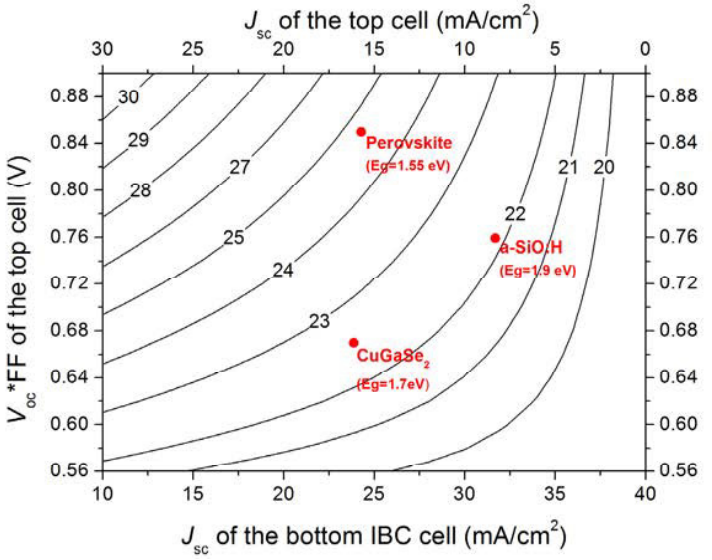


Fig. 4. (a) V_{oc} and FF of the IBC cell as a function of J_{sc} and (b) the product of $V_{oc}\cdot$FF as a function of J_{sc} as well as the fitting equation.



	a-SiO:H	$CuGaSe_2$	Perovskite
V_{oc} (V)	1.042	0.921	1.13
FF	0.73	0.73	0.75
V_{oc} *FF (V)	0.76	0.67	0.85
J_{sc} (mA/cm^2)	8.26	16.16	15.78

Fig. 5. Possible efficiency (numbers on the curves) of a hybrid tandem module with different thin-film top cells. The V_{oc}, FF and J_{sc} of the three different top cells are indicated in the table.

4. Conclusion

Our optical simulation and design have shown that it is possible for the hybrid tandem module to generate a J_{sc_sum} of over 40 mA/cm^2 by introducing thin-film solar cells onto the module glass of a IBC module. In order to achieve this high current output, the antireflective structure of pyramid-like textures is implemented to the module glass. In addition, IO:H which has good conductivity and very low near-infrared absorption is chosen as the transparent electrode for both front and back of the thin-film top cells. Our methodology to estimate the efficiency of the hybrid tandem module, which is mostly based on practical solar-cell parameters, shows the efficiency increase that three different thin-film technologies can lead to. Starting from a IBC module with an efficiency of 19.5%, the possible efficiency gain is about 2.5% for a-SiO:H top cells and about 3% for $CuGaSe_2$ top cells. Utilization of a perovskite top cell in a hybrid tandem module can result in an absolute efficiency gain of over 5%. With this structure it is possible to achieve a module efficiency of over 24% with this 4-terminal hybrid tandem module concept using state-of-the-art materials.

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