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A Non-traditional Technique Raising Efficiencies for All Kinds of Solar Cells

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Abstract: A VSM (V-Shaped Module) technique is effective for boosting the efficiencies of solar cells, which has been confirmed by several research groups in Europe and America. In this study, a 60% efficiency enhancement due to the VSM technique is obtained for solar cells with the fewest possible defects, which is verified under direct sunlight illumination. The following three mechanisms are proposed to explain the enhancement: (1) infrared photons emitted from the cells due to the law of energy conservation, (2) residual reflection which cannot be eliminated by an antireflection coating, and (3) photons reflected from electrode metal. At least, the reflection from the cells contributes to the easy-to-reproduce VSM enhancement effect. In the VSM, each tilted cell is a second source of incoming energy for the opposite cell. Due to light trapping, the 3D (Three-Dimension) configuration enables the VSM technique to increase efficiencies for all kinds of solar cells. The VSM technique, which has broken new ground in raising the efficiencies of solar cells, has opened new avenues in area-limited solar-energy applications such as concentrator solar cells, sun tracking solar panels, solar-powered vehicles, and even photodetectors etc.

Key words: Solar cells, clean energy, photovoltaic module, V-shaped configuration.

1. Introduction

The use of fossil and oil fuels has contributed to environmental pollution, but solar energy is a clean energy source and is inexhaustible. Solar PV (Photovoltaic) technology, which converts sunlight directly into electricity, is one of the fastest growing clean energy technologies. Solar PV technology appears to be one of the potential solutions for current energy needs and to combat greenhouse gas emissions. Various techniques have been used to optimize PV system performance. For PV solar cells, the improvement in power-conversion-efficiency (η) is one of the most critical challenges.

A VSM (V-Shaped Module) method has broken the traditional conceptions of generating electricity through solar cells. The VSM technique, one kind of 3D (Three-Dimension) solar cell structure, has been proven to enhance η of solar cells fabricated using mono-crystalline silicon with defects [1]. In addition, the VSM technique has been used to promote the performance of several types of solar cells [2-5]. Especially, the experimental data obtained at Stanford University have exhibited that a 52% η enhancement has been achieved by the VSM technique for thin-film solar cells [3]. Also, the studies of European researchers have demonstrated that an η increase exceeding 50% has been achieved due to the VSM technique for polymer organic solar cells [2].

According to the research results achieved at the Massachusetts Institute of Technology, 3D PV structures made of commercially available solar cells can generate measured energy densities much higher than flat PV modules [6]. In addition, Canadian researchers have tested the VSM arrays made of commercially available polycrystalline silicon solar cells under direct sunlight irradiation, and the experimental characterizations have demonstrated that the VSM arrays obtain substantially higher generated

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electrical power density than flat-panel arrays at mid-day hour [7].

2. Research Ideas

In the viewpoint of Li et al. [1], the performances of the VSM are explained on the basis of the sub-band-gap-excitation processes resulting from the defects in the solar cells. This work was planned to investigate the VSM by employing the solar cells with the fewest possible defects in order to study the effect of defects on the η of the cells in the VSM. Thus, the most perfect possible wafers were considered as starting materials for fabricating solar cells. As is well known, the purity of silicon materials can reach to a very high level due to the development of VLSI (Very Large Scale Integrated) circuits. Mono-crystalline silicon with very high purity is thus a good material for fabricating the solar cells in this work.

3. Experimental Procedures

Two 1-cm-square monocrystalline silicon solar cells having same characteristics were chosen as experimental samples in this work. Fig. 1 shows the surface photograph of one of the cells. The two cells were fabricated by using polished, dislocation-free, high purity silicon wafers. The ARC (Antireflection Coating) of the solar cells is a single-layer of SiO_2 (Silicon Dioxide) with ~100 nm thickness, which is one of widely used ARC for commercial silicon solar cells. The processing for fabricating the cells was just the well-known conventional cell process.

The two cells were tilted and were further installed to form the VSM, as shown in Fig. 2. The angle included between the two cells is called opening angle (α). For a special α value of 180°, the VSM becomes a planar module. The measured results for the planar module were used to make a comparison.

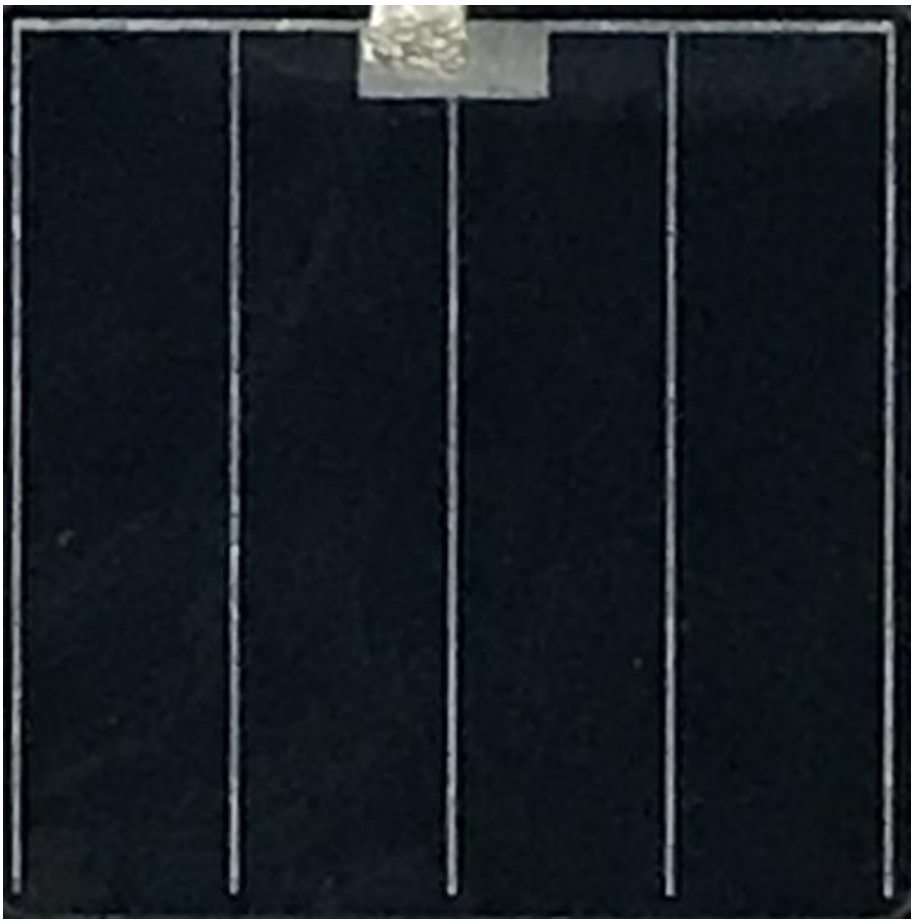

Fig. 1 The surface photograph of one of mono-crystalline silicon solar cells.

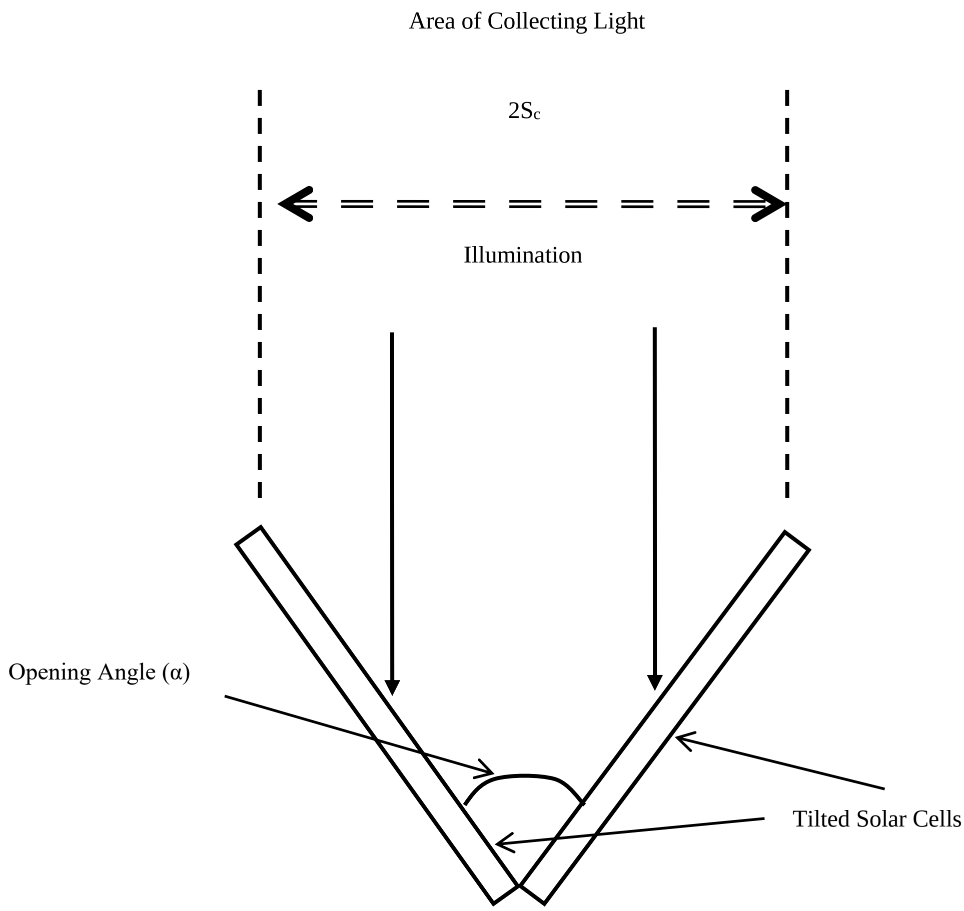

Fig. 2 A schematic cross section of the VSM structure.

Following the procedure and manner of the measurement described in Ref. [1], the solar cells were measured under 1-sun, air mass 1.5 (AM1.5) illumination at 25 ℃ in a solar simulator which was calibrated by using a standard solar cell.

4. Experimental Results

For each tilted cell in the VSM, collecting light area (S_c) is cell area multiplied by Sin ($\alpha/2$). One of the tilted cells was measured at first. S_c, short-circuit current per unit collecting light area ($J_{sc\text{-}c}$), open-circuit voltage (V_{oc}), fill factor (FF), η, and the increment in η over the one for flat way ($\Delta\eta/\eta$) of the measured cell for various α values are listed in Table 1. Note that η of the cell increases with decreasing α. Especially, the VSM technique enables η of the cell to increase from 11.2% (flat way with α = 180°) to 17.9% (α = 20°), giving a 59.8% (approximately 60%) increase in η.

For further measurements, the performances of the second cell in the VSM were identical to those of the first cell. Moreover, the two cells in the VSM were electrically connected in parallel for the measurement of parallel connection. In this way, total input solar power is incident sunlight power density multiplied by collecting light area of two cells ($2S_c$). η of the two cells in parallel connection is the output electric power divided by the total input solar power. The performances of the VSM with parallel connection were same to those of each tilted cell.

To achieve more reliable results, outdoor measurements for the VSM were also made under direct sunlight illumination. The outdoor measurements verified the easy-to-reproduce η increment effects.

In addition, the EQE (External Quantum Efficiency) of each cell in the VSM was measured. Fig. 3 shows the EQE results for several α values (20°, 50°, 90°, and 180°). It is seen that the VSM technique can significantly enhance EQE.

After the measurements, the cells were analyzed by means of HRTEM (High-Resolution Transmission Electron Microscopy). Fig. 4 shows a HRTEM image of the silicon substrate in one of the cells. The HRTEM analysis demonstrates that no defects are observed. This means that the density of stacking faults in the silicon substrate of the cell is below the detection limit (10^4 cm^{-2}) of HRTEM.

Table 1 Measured performances of the solar cells in the VSM with various α values.

α (degree)	S_c (cm^2)	J_{sc-c} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)	$\Delta\eta/\eta$ (%)
20	0.17	44.10	533	76.3	17.9	59.8
30	0.26	40.82	545	76.3	17.0	51.8
40	0.34	37.33	547	76.1	15.5	38.4
50	0.42	34.01	553	75.3	14.2	26.8
70	0.57	31.21	564	74.8	13.2	17.9
90	0.71	29.85	565	74.3	12.5	11.6
120	0.87	27.21	569	73.7	11.4	1.8
180	1.0	26.79	574	72.8	11.2	0

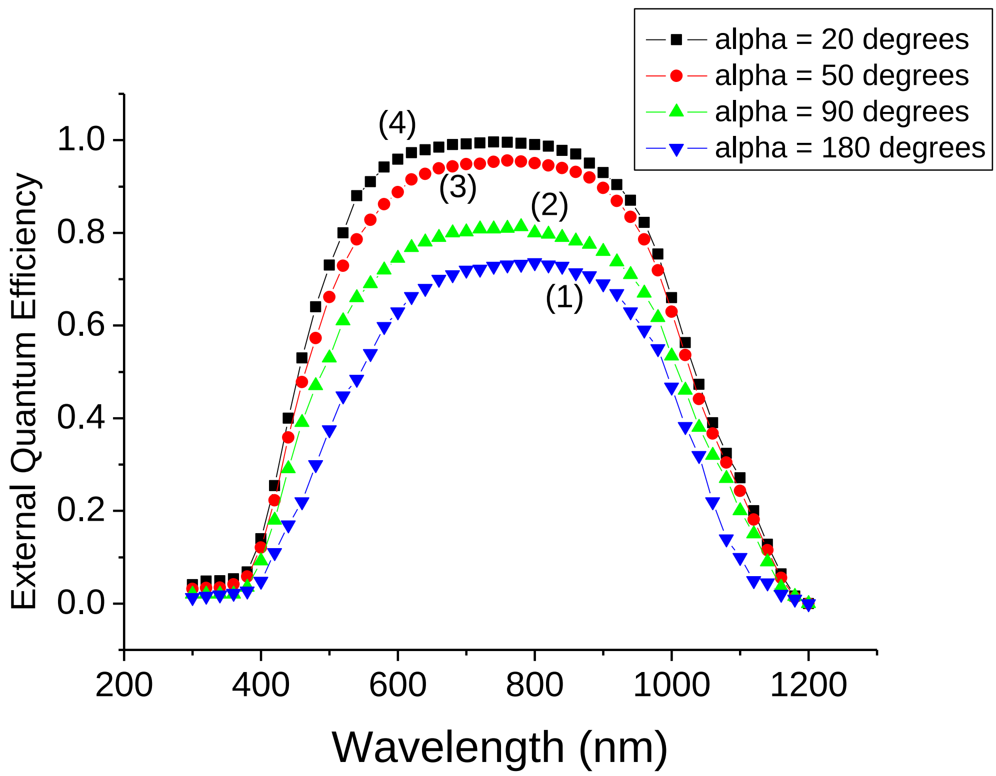

Fig. 3 EQE curves of the VSM with α (alpha) values for (1) α = 180°, (2) α = 90°, (3) α = 50°, and (4) α = 20°.

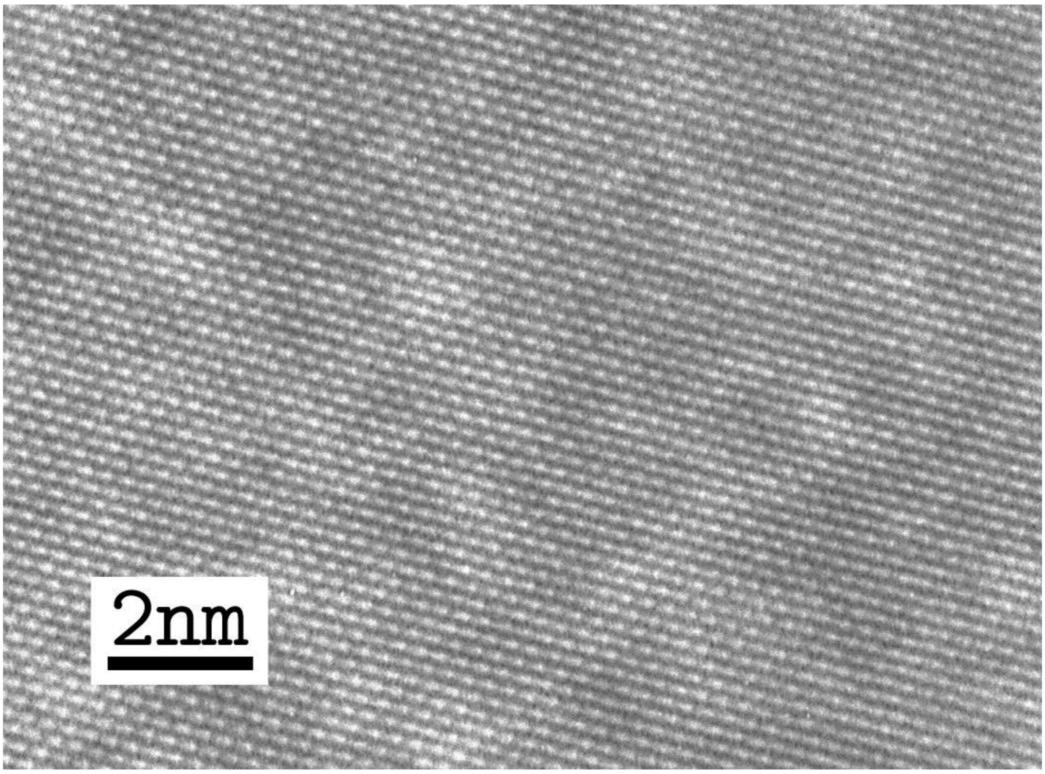

Fig. 4 HRTEM image of the silicon substrate in the solar cell.

5. Discussions

In order to explain the VSM enhancement effect, the following mechanisms are proposed.

The reflection from the cells in the VSM is considered first. The reflection consists of following two components: (1) photons reflected from contact electrode metal, and (2) a residual reflection which cannot be eliminated by ARC.

As is well known, any solar cell has contact electrode metal. The VSM results in the reflection from contact metal onto the opposite cell, contributing to the VSM enhancement effect.

Now the reflection from ARC is taken into account. It is a well-known fact that reflections will inevitably occur when light propagates across an interface between two materials with different refractive indices. The reflectance from a polished silicon cell without ARC ranges from 50% in the blue to 30% in the red, and the solar spectrally-weighted reflectance is about 35%. Various ARC approaches have been developed in order to get minimum reflection from cell surface [8-10]. However, it is unable to achieve 100% elimination of reflection. It is also known that a single-layer of SiO_2 with ~100 nm thickness not only is an excellent surface passivation to silicon surface but also acts as an ARC. The ARC used in this study can much reduce the reflection losses, which enables the spectrally-weighted reflectance to reduce to about 15% [8-10]. The V-configuration redirects the light reflected from the ARC onto the facing cell, contributing to the VSM enhancement effect.

According to the surface photograph shown in Fig. 1, the top contact metal coverage of each cell in this study is around 5% of the cell area.

The reflection from ARC and the top electrode metal is thought to be around 20%. The fact that the V-configuration enables η of the cells used in this study to increase by 60% means that some factors besides the reflection cause η improvement. Apart from the reflection from the cells, some mechanisms should be proposed to make contributions for explaining the boost in η. Thus, a hypothetical mechanism is proposed as follows.

A down-conversion theory is discussed here. It is well known that any object at a temperature emits infrared photons due to blackbody radiation. Light illumination makes any solar cell warmer, enhancing the infrared emission.

For a solar cell under the condition of steady state for equilibrium, the incident solar energy entering the cell must be exactly equal to the total energy output from the cell. Thereby, some of energy into the cell is converted into electrical power out of the cell. The surplus energy is released from the cell, mainly as infrared emission, under the constraint of energy conservation.

It is the law of the conservation of matter that some of visible photons incident into a solar cell are down-converted into emitted invisible infrared photons. The infrared emission is supposed to make a contribution to the VSM enhancement effect. The infrared contribution is supposed as follows.

It is known that a dislocation-free silicon wafer means that the density of dislocations in the wafer is below 10^4 cm^{-2}. Indeed, the substrates of the solar cells in this study contain such few defects that no defects are observed by using HRTEM with the detection limit of 10^4 cm^{-2}.

In fact, there is no absolutely pure material, and any material contains intrinsic material-impurities which induce defects. Accordingly, the light absorbers of the solar cells in this study contain unavoidable defects. Such few defects in the solar cells create intermediate levels in forbidden energy band-gap and enable the occurrence of infrared absorption through the sub-band-gap excitations shown in Fig. 5.

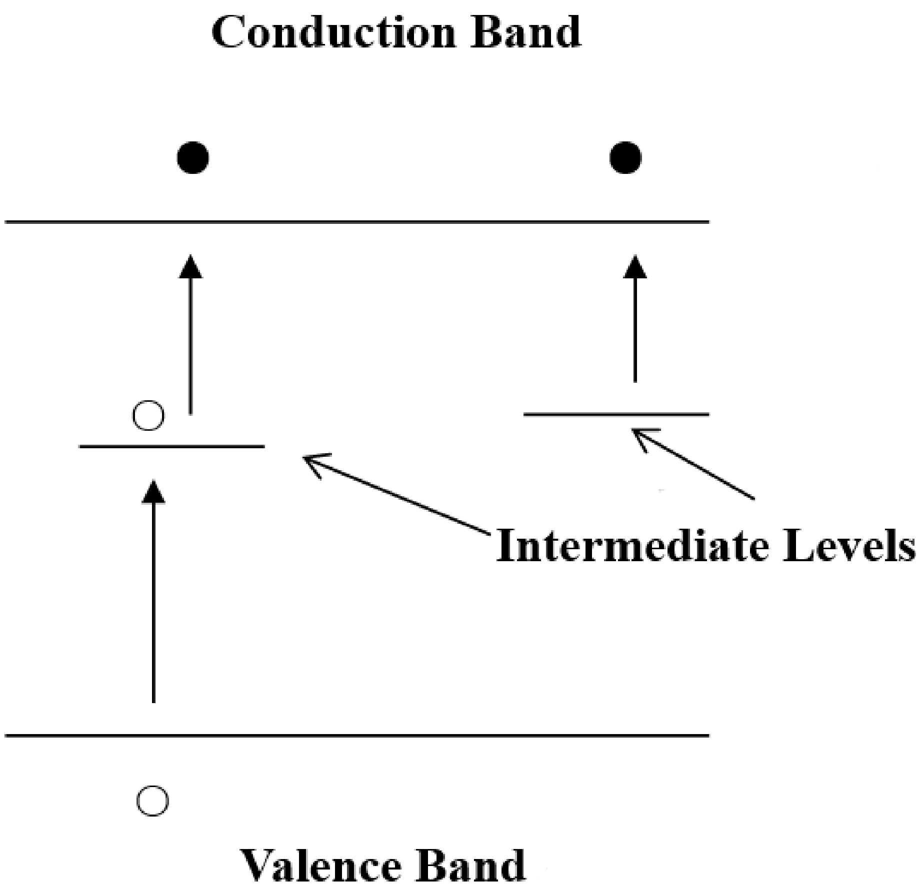

Fig. 5 The sub-band-gap excitation mechanism via the intermediate levels within forbidden gap.

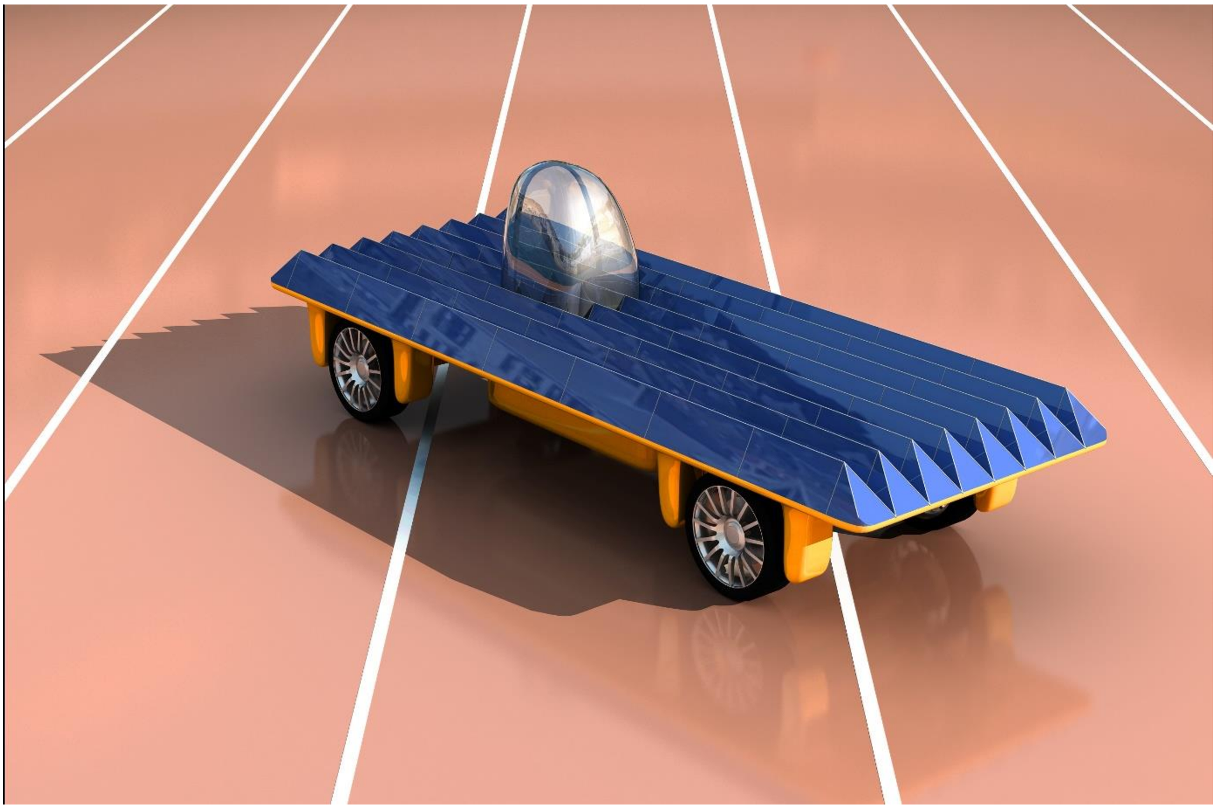

Fig. 6 The image of a solar car with the VSM technique (The picture was made by using 3D Max software [13]).

In theory, each cell in the VSM can collect some of the infrared photons emitted from the opposite cell and can produce carriers through the sub-band-gap-excitation processes, resulting in light trapping.

In the VSM, some of the infrared photons in a cell can be reflected from back metal contact in a direction such that they will strike the opposite cell and have more opportunities to be absorbed. In this way, the rear metal reflectors of the both cells in the VSM can enhance the light trapping.

The infrared emission of solar cells is thought to be one of the major loss processes by which photon energy is wasted in conventional flat modules. The V-configuration could substantially reduce these energy losses through trapping the infrared emission, contributing to the VSM enhancement effect. Although the cells used in this work contain such few defects, the sub-band-gap-excitation processes are proposed to occur in the cells.

The VSM with smaller α should be more effective for trapping the photons released from each cell. Accordingly, it is explainable that the cell improvements in both η and EQE due to the VSM technique can be enhanced with decreasing α.

The combined use of the several mechanisms discussed above is suggested to explain the VSM enhancement effect. Each of the above mechanisms is proposed to make a large or small contribution to the boost in η.

6. Conclusions and Perspectives

In the VSM, the light trapping scheme makes the two cells enhance each other. Besides the reflection from the cells, some physical principles in the VSM occur. The infrared emission from each cell thus is proposed to make a contribution to explaining the boost in η. As to the proposed infrared emission, the fundamental basis is energy conservation which is a universal law that everything must follow. It is assumed that the η boost effect of the VSM is mainly attributed to the infrared radiation emitted by each cell and collected by the facing cell. The few defects in the solar cells used in this study are supposed to play a significant role in boosting η of the cells in the VSM.

In the VSM, each tilted cell is a second source of incoming energy for the opposite cell. Due to the light trapping, the 3D configuration enables the VSM technique to raise efficiencies for all kinds of solar cells.

As is well known, a great variety of materials types (inorganic and organic materials; crystalline, polycrystalline, and amorphous materials) can serve as the light absorbers of solar cells, resulting in various solar cells which have built-in electrostatic fields to separate photo-generated carriers for creating photocurrent [11, 12]. Among all kinds of semiconductor materials, the silicon material used in this work is believed to contain fewer defects than other materials. According to the experimental results in this work, the VSM technique increases efficiencies for all kinds of solar cells.

The VSM method has opened new avenues for increasing generation power densities in area-limited PV cell applications such as concentrator cells, solar-powered vehicles illustrated in Fig. 6 [13], sun tracking solar panels, and even photodetectors etc.

A lot of studies on various solar cells are being underway towards the large reduction of PV costs. One approach is to manufacture solar cells using semiconductor materials with the lowest possible purity. For example, polymer organic solar cells do not require high-purity materials and thus have great potential to significantly reduce costs. In addition, it is possible to much reduce PV energy cost through developing silicon solar cells fabricated by using low-cost low-purity silicon material [1, 13].

In fact, the costs of various commercial solar cells have been greatly reduced for years. For instance, the price of silicon solar cells was 19 $/W in 1980, but the price has been greatly reduced and is predicted to be less than 1 $/W in 2040 or beyond [14]. As is believed, a kind of solar cells can be very cheap in the fullness of time, making the VSM method a more promising technique.

Conflict of Interest

This is to certify that this manuscript does not make any conflict of interest with any person or institution or laboratories or any work.

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