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Investigation on Open-Circuit Voltage of an Efficiency-Boosting Solar Cell Technique Featuring V-Configuration

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Abstract

The V-Shaped Module (VSM) solar cell technology, which breaks the traditional concept of solar cell system, has been proven to enhance power conversion efficiency of some solar cells and has offered opportunities to increase generation power densities in area-limited applications. Compared to a planar cell system, the VSM has an additional opportunity to absorb photons and taps the potential of solar cells. In this study, the VSM, the proposed common technique enhancing efficiencies of various solar cells, was investigated by using commercially available multi-crystalline silicon solar cells. The VSM technique enables the efficiencies of the multi-crystalline silicon cells to increase from 13.4% to 20.2%, giving an efficiency boost of 51%. Though the efficiency of the cells increases, the open-circuit voltage of the cells decreases owing to the VSM technique. Furthermore, the obvious reduction in open-circuit voltage in the VSM was found and the phenomenon is explained for the first time.

Keywords

Solar Cells, Multicrystalline Silicon, Light Trapping, Infrared Emission

1. Introduction

The V-Shaped Module (VSM) technique, one kind of three-dimension (3D) solar cell structure, has been proven to enhance power conversion efficiency (η) of monocrystalline silicon solar cells and has led to an increase of 31% in η [1]. Also, the VSM technique can increase the generation power density of polycrystalline solar cells [2]. The experimental data achieved at the Massachusetts Institute of Technology have demonstrated that 3D solar cells can generate measured energy densities (energy per base area, kWh/m^2) higher by a factor of 2 - 20 than flat photovoltaic (PV) panels [3]. In addition, the VSM arrays made of commercially available silicon solar cells were tested under direct sunlight illumination in California, USA and the experimental characterizations showed that "the V-groove array obtains the highest generated electrical power densities at mid-day hours" [4].

The VSM technique not only offers opportunities to increase generation power densities in area-limited applications such as concentrator cells, photodetectors, and solar-powered vehicles illustrated in [5], but also could find an application combined with an artificial phototropic system based on nanostructured polymers [6]. Furthermore, the VSM technique has been proposed to be the common technique enhancing efficiencies of various solar cells [5].

For small molecular weight and polymer organic solar cells, the VSM technique substantially results in η enhancements [7] [8] [9] [10]. In addition, the experimental data achieved at Stanford University have demonstrated that VSM leads to the reduction in the open-circuit voltage (V_{oc}) of organic solar cells [8].

This work was planned in detail to investigate the V_{oc} of VSM by employing commercially available multicrystalline silicon solar cells.

2. Experimental Details

Two commercially available 1-cm-square 13.4% efficient multi-crystalline silicon solar cells with same properties were chosen as experimental samples in this study. As shown in **Figure 1**, the two cells were tilted and were further installed to form the VSM. **Figure 2** shows the image of the real VSM structure. The angle included between the two tilted cells is called opening angle (α). For a particular α value of 180˚, the VSM becomes a conventional manner (planar configuration).

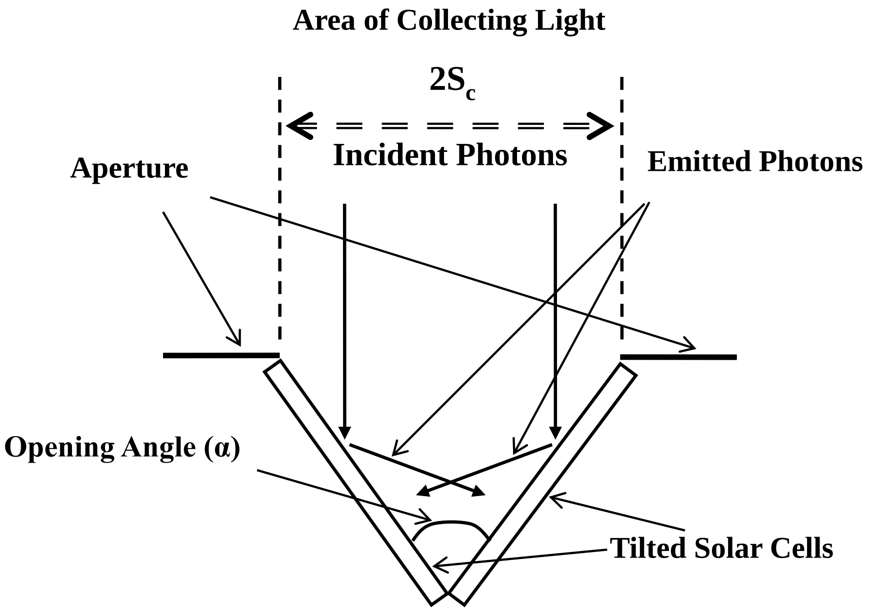

Figure 1. A schematic cross section of the VSM structure.

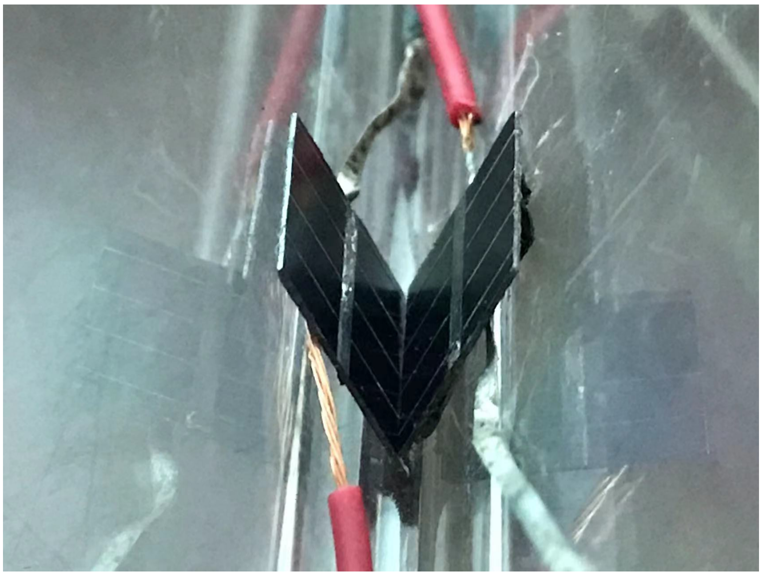

Figure 2. The image of the real VSM structure.

The measured results for the conventional manner were used to make a comparison. The collecting light area for each tilted cell is cell area multiplied by Sin($\alpha/2$).

Following the procedure of the measurement described in [1], incoming light was projected along the symmetrical line of the VSM. The VSM was measured for various α values. The tilted cells were measured under 1-sun, air mass 1.5 (AM1.5) illumination in a solar simulator.

3. Results and Discussion

One of the tilted cells was measured first for various α values. The short-circuit current per unit collecting light area ($J_{sc\text{-}c}$), V_{oc}, fill factor (FF), η, and the increment in η over the one for flat way ($\Delta\eta/\eta$) are listed in **Table 1**.

From **Table 1**, we see that the VSM technique enables the η of the cell to increase from 13.4% to 20.2%, giving a η boost of 51% ($\Delta\eta/\eta$). Though the η of the cell increases with decreasing α, V_{oc} reduces with decreasing α. Especially, an obvious reduction in V_{oc} was found for the VSM with an α value of 20 degrees.

The second cell in the VSM was measured for the same α values as the first cell. The measurements show that the testing results of the two tilted cells were identical. Moreover, the two tilted cells in the VSM were electrically connected in parallel. In view of the luminous flux into the collecting light area (equivalent aperture area), the performances of the VSM with parallel connection were identical to those of each tilted cell.

In order to gain more reliable results, outdoor measurements for the VSM were also made under direct sunlight irradiation. The outdoor measurements verified the VSM effect.

To explain the efficiency boost due to the VSM technique, the following three mechanisms are proposed.

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

α (degrees)	S_c (cm^2)	$J_{sc\text{-}c}$ (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)	$\Delta\eta/\eta$ (%)
20	0.17	57.6	522	67.2	20.2	51
30	0.26	52.6	537	67.6	19.1	42.5
40	0.34	47.3	545	69.4	17.9	33.5
50	0.42	44.2	555	70.5	17.3	29
70	0.57	37.9	561	71.1	15.1	13
90	0.71	35.3	569	71.2	14.3	6.7
120	0.87	32.9	575	71.3	13.5	0.7
180	1.0	32.4	580	71.3	13.4	0

First mechanism is based on the reflection from antireflection coating (ARC). It is well known that a bare Si surface reflects back about 35% of the incident sunlight and a single ARC layer reduces the spectrally-weighted reflection to about 10%. The ARC of the cells in this study is a single layer of silicon nitride [11], which is a widely used ARC technique for commercial silicon cells. The reflection from the cells is inevitable. The VSM results in the reflection from one cell onto the other cell, contributing to the improvements in η.

Second mechanism is based on the reflection from metal top contact grids of solar cells. For conventional solar cells, metal top contact grids for front electrodes shadow 3% - 12% of sunlight, depending upon design. The metal contact coverage of the cells in this study is less than 10% of the cell area, which is a common design for commercial cells. The VSM leads to the reflection from the metal contact onto the opposite cell, contributing to the improvements in η.

Third mechanism is a hypothesis which is based on the law of the conservation of energy. In fact, most of the incident sunlight enters the silicon cells used in this study. The third mechanism is proposed as follows.

A transformation (down-conversion) theory is first discussed in detail. As is well known, the vibratory motion of the electrical charges in an object containing atoms (composed of electrons and atomic nucleuses) leads to thermal radiation (infrared emission) which is called blackbody radiation, and any object at a temperature emits infrared (IR) photons. Light illumination makes any object warmer, enhancing IR emission.

For a solar cell under the condition of steady state for equilibrium, the incident energy falling on the cell must be exactly equal to the total energy output from the cell. Accordingly, a fraction of energy into the cell is converted into electrical power out of the cell. The surplus energy is released from the cell, mainly as IR emission, under the constraint of energy conservation. In principle, a visible photon incident into a solar cell can be down-converted into numerous IR photons for thermal radiation.

In the VSM system, a portion of incident visible photons can be in principle converted into carriers through the following three steps. First, the incident visible photons are absorbed by each cell. Second, the absorbed visible photons are down-converted into emitted IR photons. Finally, the opposite cell absorbs some of the emitted IR photons and produces carriers due to the sub-band-gap-excitation processes resulting from the grain boundaries (containing numerous defects) in the multi-crystalline cells.

Because the VSM technique results in an efficiency boost of 51%, it is assumed that the efficiency increment effect is mainly attributed to the IR radiation emitted by each cell and collected by the facing cell. The numerous defects in the grain boundaries of the multi-crystalline silicon solar cells are thus supposed to play a significant role in boosting efficiencies of the cells in the VSM.

In general, the three kinds of mechanisms are suggested in this study: 1) a residual reflection which can not be eliminated by ARC; 2) photons reflected from top contact metal; and 3) infrared photons converted from visible photons. In the third mechanism, the fundamental basis is the energy conservation which is a universal law that all natural phenomena obey. Each of the three mechanisms is proposed to make a large or small contribution to the efficiency boost. The combined use of the three mechanisms is suggested to explain the efficiency boost due to the VSM technique.

The VSM technique could substantially reduce energy losses through trapping the IR emission and the reflection from ARC and the metal top contact. The VSM with smaller α should be more effective for reducing these energy losses. Thereby, it can be explainable that the cell improvements in η due to the VSM technique can be enhanced with decreasing α.

Compared to a flat panel, the VSM has an additional opportunity to absorb light and taps the potential of solar cells. According to the explanation, each cell in the VSM is a “second” source of incoming energy for the opposite cell, and the two tilted cells enhance each other.

The V_{oc} reduction could be interpreted as follows. Light-generated voltage is dependent on the luminous flux density (light intensity) for a cell. When a solar cell is tilted, the sunlight flux into it is reduced due to the decreased area of collecting light, and the sunlight flux density for cell surface area is reduced. Although each tilted cell in the VSM receives both sunlight and the photons coming from the opposite tilted cell, the received photons might not compensate the reduction of the sunlight flux. Accordingly, the measured V_{oc} reduction is explainable.

4. Conclusion

The combination of the cell IR emission and the reflection from ARC and the metal top contact is proposed to explain the efficiency boost due to the VSM technique. Though η of the cell increases with decreasing α, V_{oc} reduces with decreasing α. In this study, the obvious reduction in V_{oc} of solar cells in the VSM was found and the phenomenon is explained for the first time. The VSM technique makes only one change from a flat panel to a V-shaped configuration. It is very easy to test the VSM effect by using commercial solar cells. The VSM technology is applicable to practice in area-limited applications.

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Conflicts of Interest

It is certified that this manuscript does not make any conflicts of interest with any person, institution, laboratory or any work.

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