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Thermal and electrical performance analysis of silicon vertical multi-junction solar cell under non-uniform illumination

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ABSTRACT

The silicon vertical multi-junction (VMJ) solar cell has low costs and low series resistance, thus it has a good potential in concentration photovoltaics. However, there were few discussions about the thermal and electrical performance of silicon VMJ cell under non-uniform illumination. In this work, the thermal performance of silicon VMJ cell under 1D non-uniform illumination of 500 suns was calculated using finite element method first, and then the electrical performance of the cell was calculated using SPICE software based on the thermal simulation results. It was found that the mean temperature of the cell increased with the degree of non-uniform illumination when the area ratio of the sink to the cell was 500X, and the mean temperature changed few when the area ratio was 2500X. The efficiency of the cell did not decrease with the increase of the degree of non-uniform illumination when the area ratio was 500X, and the efficiency increased with the degree of non-uniform illumination when the area ratio was 2500X. Thus, the silicon VMJ cell had better performance than silicon planar junction cell under 1D non-uniform illumination of 500 suns.

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1. Introduction

Photovoltaics (PV) is being paid more and more attention as a kind of renewable energy, lots of work is being done to decrease the costs of solar cells, the concentration photovoltaics (CPV) is becoming more and more competitive as a kind of third generation photovoltaics [1–5]. The silicon vertical multi-junction (VMJ) solar cell which has low series resistance and low costs has a good potential in CPV [6], the efficiency of the cell has reached 19.19% under 2480 suns [7], simulation results showed that the efficiency of the cell would reach close to 30% under 1000 suns after optimizing the device parameters of the cell [8–10]. However, above simulation work on VMJ cell was all based on the assumption that the VMJ cell was under uniform illumination, and non-uniform illumination was inevitable in realistic CPV systems, the non-uniform illumination was caused by many factors, such as concentrator optics, improper tracking and so on [11]. Lots of experiment and simulation work has been done to analyze the effect of non-uniform illumination on the electrical and thermal performance of other solar cells [11]. The non-uniform illumination profiles on the cells were complex in realistic CPV systems, the Gaussian function was always used to characterize the profiles in theory. Vishnoi et al. studied the effect of non-uniform illumination on the electrical performance of silicon planar junction cell by simulation and experiment, they found that the short circuit current density (J_{sc}), open circuit voltage (V_{oc}) and efficiency of the cell decreased with the area of the illuminated region of the cell, because the dark region of the cell worked as a load [12]. Luque et al. calculated and tested the thermal and electrical performance of silicon planar junction cell under 1D non-uniform illumination, they found that the temperature of the center of the cell increased, the V_{oc} of the cell decreased a few, the fill factor (FF) and efficiency of the cell decreased badly under non-uniform illumination, because the electrical losses of the center of the cell caused by series resistance increased. They also found that the edge of the cell became less

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active under non-uniform illumination, because the illumination intensity of the edge decreased. The quality of the edge of the realistic cells was always poor, thus the non-uniform illumination also had positive effect [13]. Mellor et al. calculated the electrical performance of silicon planar junction cell under 1D non-uniform illumination using finite element method [14], Herrero et al. tested the electrical performance of III-V multi-junction cell under 2D non-uniform illumination, they also found that the V_{oc}, FF and efficiency of the cell decreased with the increase of the degree of non-uniform illumination [15]. Araki et al. calculated the electrical performance of III-IV multi-junction cell under 1D non-uniform illumination using a distributed circuit model, they found that the J_{sc} of the cell decreased with the increase of the chromatic aberration of non-uniform illumination [16].

Sater et al. have made a 500X CPV system which used the VMJ cells as the receivers, they focused the sunlight reflected by many mirrors to two receivers. The final illumination patterns on the VMJ cells were line-focused although the system was point concentration, thus the illumination on the VMJ cells was non-uniform along one direction and nearly uniform along another vertical direction [17]. Segev et al. calculated the electrical performance of the module made of silicon VMJ cells under 2D non-uniform illumination, they found that the module made of silicon VMJ cells had an obvious advantage over the module made of silicon planar junction cells [18]. However, Segev et al. didn't discuss the electrical performance of a single VMJ cell under non-uniform illumination, and they didn't consider the heat generated in the cells [18]. The heat was also inevitable in realistic CPV systems [17], but there was very few simulation and experiment work about the effect of non-uniform illumination on the thermal and electrical performance of the VMJ cell. Thus the thermal and electrical performance of the VMJ cell under 1D non-uniform illumination of 500 suns was calculated and analyzed based on Segev et al.'s device parameters [18], and the performance of the cell under uniform illumination was also calculated to compare in this work. The temperature profiles of the VMJ cell under uniform and 1D non-uniform illumination were calculated using finite element method first, and then the electrical performance of the cell was calculated based on the temperature profiles using SPICE software, and the performance of the cell under 300 K room temperature was also calculated to compare.

2. Structure and models

The passive cooling was used in this work as Sater et al. did [17], the VMJ cell was mounted on the center of an aluminum flat sink to simplify the simulation, as shown in Fig. 1 (a). The volume of the sink could be made smaller by using more complicated structure, the insulating layer between the cell and sink in realistic CPV systems was ignored here. The sizes of the cell and sink varied freely in our simulation although the area ratio of the sink to the cell was always set close to the concentration ratio of the system, the thickness of the sink was set to 4 mm which was close to the thickness of the sinks in realistic CPV systems [19,20]. The cell and sink were assumed to be square to simplify the discussion, thus we used their side lengths to represent their sizes, and a quarter of the cell and sink was simulated in this work according to the symmetry of the cell and sink. The illumination on the cell was set to be uniform along X direction, which was the direction of current flowing in the cell, and the illumination was set to be only non-uniform along Y direction, which was perpendicular to X direction, thus the illumination intensity of each sub-cell of the VMJ cell was equal [17]. The Gaussian function was used to characterize the 1D non-uniform illumination profile as follows [14,21]:

$$P_{illumination} = P_m \times A_m \times \exp\left[\frac{-y^2}{\left(2S_0^2\right)}\right] \tag{1}$$

which indicated that the illumination intensity of the center of the cell was the highest and that of the edge was the lowest. The S_0 in formula (1) was the shape factor, A_m was the normalization factor, P_m was the average illumination intensity. The degree of non-uniform illumination increased with the decrease of S_0, A_m was adjusted with S_0 to ensure that the total illumination intensity of the cell was not changed with S_0 [14]. The P_m was determined by concentration ratio C as follows:

$$P_m = P_{1sun} \times C \tag{2}$$

where $P_{1\mathrm{sun}}$ was 1000 W/m^2 (1 sun), C was fixed to 500X which was close to the realistic concentration ratio of Sater et al.'s system [17].

The single diode model was used to characterize the basic electrical character of the VMJ cell under illumination as follows [18,22]:

$$J = J_{sc,1} \times C - J_d \times \left\{\exp\left[\frac{(V + IR_s)}{(nkT/q)}\right] - 1\right\} \tag{3}$$

where $J_{sc,1}$ was the J_{sc} normalized by concentration ratio, J_d was the dark current density, R_s was the series resistance, n was the ideality factor, k was the Boltzmann's constant, T was the absolute temperature and q was the charge of an electron. The device parameters of VMJ cell which were used by Segev et al. were used here, these parameters were introduced in detail in Segev et al.'s paper, the thickness and width of the sub-cell of the VMJ cell were set to

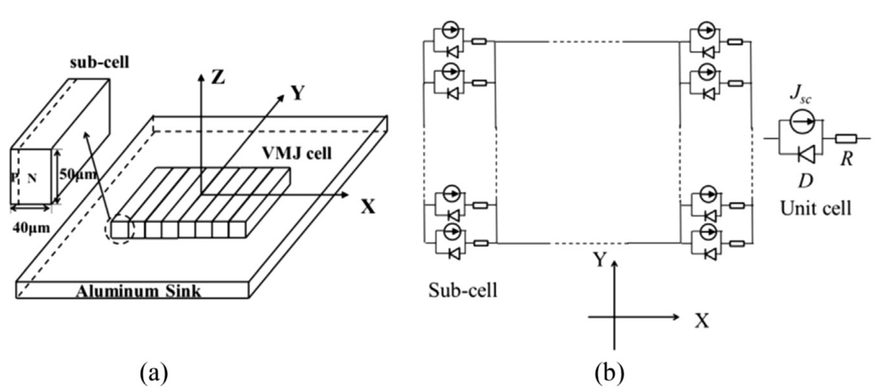

Fig. 1. The schematic of the VMJ cell mounted on the center of an aluminum flat sink (a), the circuit simulation model of the VMJ cell (b), D represents the diode character of the unit cell, J_{sc} represents the photocurrent of the unit cell and R represents the series resistance of the unit cell.

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