Analysis of high-voltage silicon vertical multi-junction solar cells: under concentrated illumination

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ABSTRACT

We analyze the J-V characteristics of silicon vertical multi-junction solar cells. The J-V characteristic data includes J_0, R_S, R_{sh}, n, and J_{ph}, representing saturation current density, series resistance, shunt resistance, ideality factor, and photocurrent density, respectively, and are utilized to extract the parameters of these multi-junction solar cells. These parameters were recently acquired in a previous investigation. In our research, we developed a MATLAB code to investigate the efficiency variation with concentration using the nonlinear least-squares method, following a similar approach as the previous study. Our findings reveal that the algorithm effectively utilizes electrical parameters obtained through the nonlinear least-squares method, ensuring stable convergence and faithful replication of experimental J-V characteristics. Our findings indicate that an increase in light concentration from 1 to 100 suns leads to an efficiency improvement from 19.4 to 26.2%. However, beyond 100 suns, the efficiency declines from 26.2 to 17.3%. The most influential parameter in determining solar cell efficiency is the open-circuit voltage, V_{oc}. Our experiments have shown an increase in this voltage with light concentration. For instance, its value changes from around 19.147 V at 1 sun to approximately 25.491 V at 500 suns.

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1. INTRODUCTION

The Si solar cell type with vertical multi-junction or VMJ exhibits higher voltage, reaching up to 120 V, while maintaining a lower current, typically less than 0.3A [1]. Previous studies [2], [3] have reported the limitations of silicon solar cells with efficiencies of η=30 and 31%, respectively. Manufactured silicon cells and modules achieve maximum efficiency of 25% and 22.9%, respectively, with an efficiency of η=42.3% recorded at 406 suns of light intensity [4]. It has been suggested that the maximum achievable efficiency for solar cells can reach 45% [5].

Additionally, a study is established that compares various techniques for optimizing the tracking of the maximum power point in photovoltaic arrays [6]. In terms of open circuit voltage, it is noted that for both types of solar cells, the single-junction silicon solar cell does not exceed 0.7 V [7], while for InGaP/InGaAs/Ge cells, it reaches up to 3 V [8]. A series of theoretical and experimental studies have explored the characteristics of solar cells in relation to series resistance [9]. The study investigates the influence of irradiation on various parameters of monocrystalline photovoltaic solar cells [10]. Various methods are suggested in the analysis of diverse solar devices, encompassing GaAs and Si solar cells [11]. Therefore, evaluating SiC-based semiconductor technologies at their practical limits is recommended to achieve greater efficiency and higher power density by increasing switching frequencies. These features are crucial for embedded applications in electric vehicles and more-electric aircraft [12]–[15].

Considering the design of solar cells, it becomes evident that understanding the impact of parameters such as temperature and radiation intensity is crucial for predicting and optimizing their behavior. This document presents a study that focuses on the modeling and characterization of the silicon-based vertical multijunction solar cell VMJ, along with investigating the influence of solar concentration on its efficiency. Acquiring precise values for the inherent parameters of the VMJ solar cell proves intricate, mainly due to the extensive interconnection of sub-cells and the heightened solar irradiance. In fact, the modeling of the VMJ cell heavily relies on the electrical circuitry of a single-junction solar cell. This approach is grounded in the observed practical similarity between the J-V of the VMJ cell and the single-junction cell. This simplifies the extraction of specific parameters (such as J_0, J_{ph}, n, R_S, R_{sh}, V_{OC}) associated with the VMJ cell by employing the Lambert W function [11] as a model for adjusting these parameters using the least mean squares (LMS) method. In conclusion, we have evaluated the influence of augmented solar concentration across the range from 1 to 500 suns on the efficiency of the VMJ cell, employing these parameters as reference points. Furthermore, the justification for the higher voltage value in this type of cells is elucidated.

2. THEORY AND MODEL

In a single junction solar cell, two cases arise for the band gap. For a narrow band gap material like germanium E_g = 0.7 eV, the cell absorbs a large portion of the solar spectrum and delivers a high current at low voltage. The output power, power out, is determined by high current x low voltage, but excessive thermalization loss occurs due to the small band gap. On the other hand, increasing the band gap of the semiconductor provides a small amount of electricity at high voltage. In this case, the output power. Power output is determined by low current multiplied by high voltage, with the low current being a result of limited spectral absorption.

The theoretical single-junction study conducted by Shockley and Queisser [2] demonstrates a traditional trade-off between efficiency and band gap for a junction solar cell. The comparison between the 'Semi-Empirical Limit' of solar cells, representing the 'Best Experimental Efficiency to Date,' and the 'Detailed Balance Limit' derived by Shockley and Queisser is provided by Shockley and Queisser [2]. The theoretical efficiencies of these multi-junction cells under concentration can be very high, as demonstrated by Dimroth and Kurtz in the article [12]. They have shown that under concentration, by increasing the theoretically number of junctions, efficiencies higher than 60% or even 70% could be achieved. For instance, for a 3J conventional configuration, η_{th} = 54.2%, for a 4J Lattice-matched configuration, η_{th} = 63.1%, and for a 6J Lattice-matched configuration, η_{th} = 58.7%. Compound III-V semiconductors are promising contenders for producing multi-junction solar cells because of two key factors, their ability to be fabricated with exceptional quality and their wide spectral coverage with often direct band gaps, resulting in high absorption coefficients. These attributes underpin the success of this technology, which has attained an impressive efficiency of 39% with GaInP/GaInAs/Ge [12] configurations, marking it as the most efficient among all photovoltaic devices for converting solar energy into electrical energy. The output power is determined through the (1).

$$\eta = \frac{V_{OC}\, I_{SC}\, FF}{P_{optic}} \tag{1}$$

Where voltage at open circuit or $V_{OC} = V_1 + V_2 + V_3$ and $I_{SC} = min\ (I_1, I_2, I_3)$.

According to (1), the two crucial parameters in calculating the output power are the short-circuit current I_{SC}, which is equal to min (I_1, I_2, I_3) and therefore has no effect on efficiency as I_{SC} increases linearly with concentration, and the open-circuit voltage V_{OC} which directly impacts efficiency. Poptic is the optical power input. However, its value is limited by the number of junctions, i.e., $V_{OC}=\sum Vi$. The primary challenge in these types of monolithically stacked multi-junction solar cells is the material selection for enhanced absorption, the optimization of each sub-cell, and finally, connecting these sub-cells through tunnel diodes that need to be both efficient conductors and transparent.

The various electric power system designs for future electric aircraft were analyzed by comparing their weight and stability, with the most promising architecture selected based on these criteria [16]. To tackle the issue of enhancing V_{OC} under high concentrations, researchers have devised a different class of solar cells. High VMJ silicon solar cells are specifically designed for effective performance under solar intensities surpassing 1000 suns AM1.5. Comprising 40 junctions connected in series, these cells generate 31.8 watts at 25.5 volts and operate at an intensity close to 2500 suns AM1.5 [17]. Other researchers [18] have demonstrated that vertical junction silicon solar cells can operate at high concentrations due to their design focused on low current and high voltage, which helps reduce losses related to series resistance. However, despite these improvements, test and analysis results have shown only modest efficiencies, hovering around 20% [18].

The vertically multiple-junction cell VMJ configuration is particularly adept at enabling efficient operation under high voltage conditions, while simultaneously maintaining low current levels. This unique combination of characteristics makes the VMJ cell highly adaptable and compatible with a wide range of energy sources, as indicated by Sater and Sater's research findings [17]. The intriguing qualities of this operational mode have sparked our curiosity and motivation to conduct an in-depth and practical study of this specific cell type. Through this study, we aim to gain precise insights into the performance and capabilities of the VMJ cell configuration, paving the way for further exploration and potential applications in the future. Vertical junction solar cells, also known as lateral, illuminated solar cells [19]-[21], are a unique type of cells.

The corresponding photocurrent density J_{ph} at a given excitation wavelength λ and light intensity I_L [22] is given by (2).

$$J_{ph} = EQE\ x\ \frac{q\lambda}{hc}\ I_L \quad (2)$$

Where external quantum efficiency (EQE) is the photovoltaic external quantum efficiency, h the Planck constant, c the speed of light, and q the elementary charge. The (2) demonstrates that the photocurrent J_{ph} is proportional to the intensity of the incident light, I_L, which itself is proportional to suns. h is the Planck's constant, c is the speed of light and λ is the wavelength of light. Therefore, in (2) can be expressed as (3).

$$J_{ph,k} = k\ x\ J_{ph,1suns} \quad (3)$$

Where *k* represents the number of suns, and *1* sun is approximately equivalent to 1000 W/m² under standard conditions and at ambient temperature. Shall we revisit the efficiency in (1) and substitute P_{optic} with k x suns and $J_{SC} \cong J_{ph,k}$ with the expression from (3). Under these approximations, in (1) transforms to (4).

$$\eta = \frac{V_{OC}\,J_{SC}\,FF}{P_{optic}} \cong \frac{V_{OC}\ \mathrm{K\ x\ J_{ph,1suns}}FF}{\mathrm{K\ x\ suns}} \cong \frac{V_{OC}\,J_{ph,1suns}FF}{\mathrm{suns}} \quad (4)$$

In (4) reveals that the coefficient 'k' disappears, indicating that the photocurrent J_{ph} generated by the concentrated photovoltaic cell VMJ does not have an impact on the efficiency η. However, it remains necessary to determine the influence of V_{OC} and fast Fourier (FF). To assess the influence of V_{OC} on the efficiency η, it is necessary to establish the relationship between V_{OC} and 'k'. This can be achieved easily by employing (3) under open-circuit conditions, wherein J = 0 A and V = V_{OC}, while assuming that R_{Sh}tends towards infinity (5) based on (6).

$$0 = J_{ph} - J_0\left(exp\left(\frac{q(V_{OC})}{nk_BT}\right) - 1\right) \quad (5)$$

$$J = J_{ph} - J_0\left(exp\left(\frac{q(V+R_SJ)}{nk_BT}\right) - 1\right) - \frac{V+R_SJ}{R_{sh}} \quad (6)$$

Finally, the relationship between V_{OC} and 'k' as in (7).

$$V_{OC} = \frac{nk_BT}{q}\ \ln\left(\frac{k\ x\ J_{ph,1suns}}{J_0}\right) = V_{oc1} + \frac{nk_BT}{q}\ln\ k \quad (7)$$

Where $V_{oc1} = \frac{nk_BT}{q}\ \ln\left(\frac{J_{ph,1suns}}{J_0}\right)$ represents the conventional V_{OC} under at one sun concentration and k is the solar concentration ratio. The (7) shows that V_{OC} increases in a natural logarithmic manner with the increase of the concentration ration 'k'. To understand the impact of concentration on the fill factor (FF) and other parameters such as J_0, R_S, and R_{Sh} of the VMJ cell, we will practically examine this using the LMS method.

3. RESULTS AND DISCUSSION

The VMJ under investigation in this study is detailed in the article [23]-[25]. In order to enhance the comprehension of the results presented in this study, we will briefly recapitulate the J-V of this cell at various light intensities. Similarly, we will also elucidate the LMS method used for parameter extraction. This method will play a central role in our approach, as it will enable us to accurately obtain and analyze the parameters necessary for our subsequent studies.

Figure 1 illustrates that silicon-based VMJ solar cells are capable of delivering high voltages of around 25 V, making them ideal for ensuring efficient operation even under light intensities surpassing 500 AM 1.5 solar intensities. This ability to generate high voltages demonstrates their robust performance and adaptability to higher light conditions, rendering them a promising choice for various solar applications. Likewise, Figure 1 highlights the almost perfect concurrence between the experimental results shown as blue circles and the least squares method represented by the red line. This close correspondence validates the reliability of the experimental data and underscores the efficiency of the least squares method in accurately modeling the observed behavior using the LMS approach.

Figure 2 demonstrates a linear increase in short-circuit current J_{SC} relative to light concentration, within the range of 1 to 300 suns, with a slope of 1.327×10^{-6} (A.m^2/W). This observation aligns perfectly with the theory demonstrated in (3). Consequently, it is established that changes in light concentration do not impact efficiency, as indicated by (4). However, beyond 300 suns, the curve J_{SC} versus concentration changes direction and tends to flatten. This indicates that the current reaches saturation, becoming independent of light concentration. Consequently, within both ranges of light concentration, the concentration-induced photocurrent does not impact the cell's efficiency VMJ.

As depicted in Figure 2, the V_{OC} exhibits a nonlinear increase with light concentration. This curve behavior could potentially impact the output power of VMJ cells based on concentration. These effects are characterized in more detail later. Moreover, V_{OC} evolves from 19.147 V to 25.491 V, transitioning from 1 sun to an irradiance of 500 suns. This observation aligns perfectly with the theoretically established in (7) mentioned earlier. The increase in concentration leads to an enhancement in conversion efficiency, driven by a more pronounced rise in voltage.

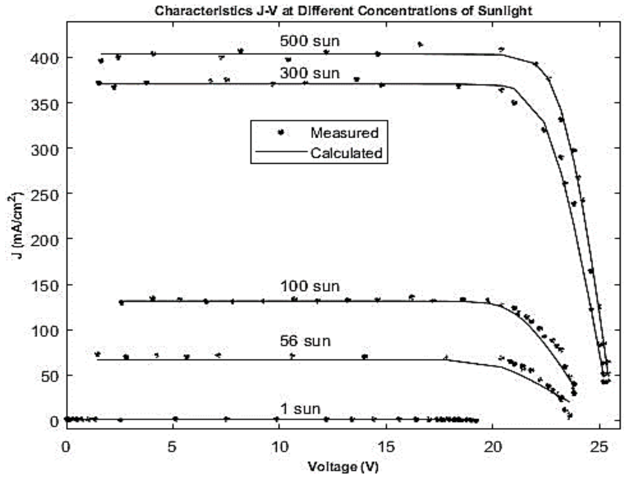

Figure 1. J-V curves for VMJ cell taken over the range of 1 to 500 suns AM 1.5 intensities

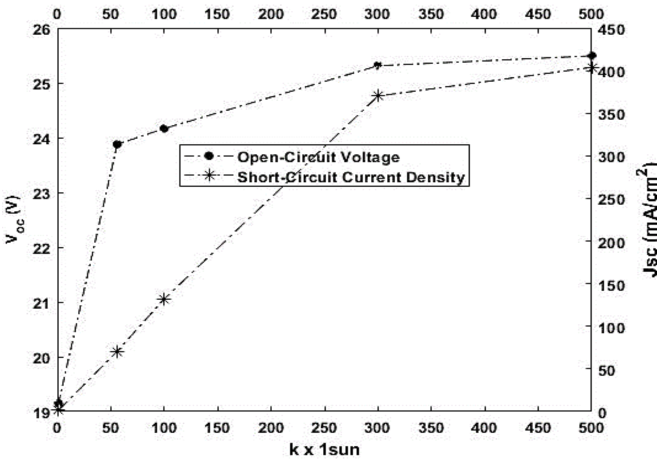

Figure 2. Variation of V_{OC} and short-circuit current vs sun concentration

To increase the efficiency of the solar cell, we need to transition to a multiple junction solar cell, and the way we do this is by stacking different materials on top of each other, each tuned to absorb a different part of the solar spectrum, as seen in Figure 3. The blue material will have a higher band gap and will be tuned to absorb ultraviolet (UV) and a portion of the visible spectrum. The green material will be used to absorb a middle portion of the solar spectrum, and the red material will have the lowest band gap and will be used to absorb a portion of the infrared (IR), as seen in Figure 3. This allows us to minimize thermalization losses as we traverse the solar spectrum.

To comprehend why the V_{OC} increases, we need to revisit the principles of photovoltaic conversion, as implemented by current devices. This conversion occurs in three steps: i) Absorption of photons with energy $h\nu > E_g$, creating out-of-equilibrium populations of electrons and holes; ii) Each carrier type rapidly reaches a quasi-equilibrium defined by a quasi-Fermi level (i.e., an electrochemical potential) E_{Fn} for electrons and E_{Fp} for holes, and their difference, $E_{Fn} - E_{Fp} = qV$ represents the recoverable energy per absorbed photon (where V is the photovoltage); and iii) The carriers, collected at the contacts before recombination occurs, contribute to the photocurrent.

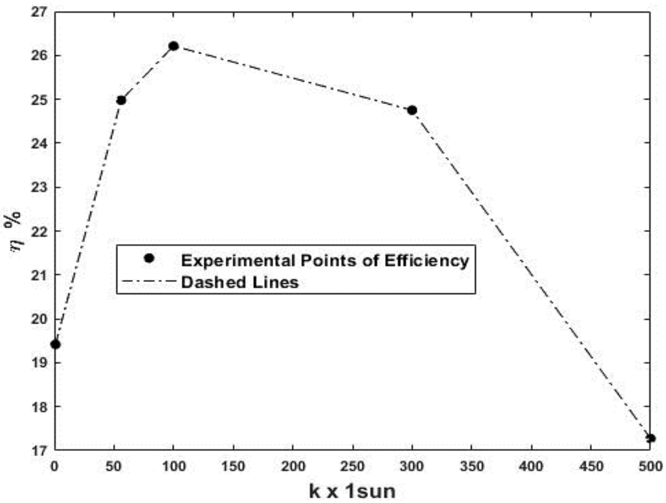

Figure 3. Efficiency vs sun concentration for solar cells VMJ

The electron density n (cm^{-3}) in the conduction band is given by (8).

$$n = N_C \, exp\left(-\frac{E_C - E_{Fn}}{k_B T}\right) \quad (8)$$

The hole density p (cm^{-3}) in the valence band is given by (9).

$$p = N_v \, exp\left(\frac{E_v - E_{Fp}}{k_B T}\right) \quad (9)$$

Where N_C and N_C are the effective densities of states. They essentially represent the number of useful states at temperature T in their respective energy bands. After performing a series of mathematical operations, in (8) and (9) yield the expressions for E_{Fn} and E_{Fp}, respectively, as (10) and (11).

$$E_{Fn} = E_C - k_B T \, ln\left(\frac{N_C}{n}\right) \quad (10)$$

$$E_{Fp} = E_v + k_B T \, ln\left(\frac{N_v}{p}\right) \quad (11)$$

The recoverable energy per absorbed photon corresponds to the difference of the quasi-Fermi levels, and this relationship is given as (12).

$$E_{Fn} - E_{Fp} = qV \quad (12)$$

As the light concentration increases, the generation of electron-hole pairs also increases. This leads to a rise in the respective densities of electrons (n) and holes (p). Indeed, in (12) demonstrates that as n increases, $\ln\left(\frac{N_C}{n}\right)$ decreases (with $N_C > n$). Consequently, the quasi-Fermi energy level E_{Fn} shifts towards E_C. Similarly, according to equation (11), the quasi-Fermi energy level E_{Fp} shifts towards E_v.

This dual shift of the two quasi-Fermi levels, as illustrated by (12), results in an increase in photovoltage V. For high concentrations (>300 suns), the value of n approaches N_C. In this case, $\ln\left(\frac{N_C}{n}\right)$ approaches zero, meaning that the shift of E_{Fn} towards the direction of E_C is weak or negligible. Similarly, when p approaches N_v, $\ln\left(\frac{N_v}{p}\right)$ tends towards zero, and thus there is no significant shift in E_{Fp}. This implies that the difference $E_{Fn} - E_{Fp}$ remains nearly constant. As a result, the variation in V at high concentrations (>300 suns) is almost negligible, as illustrated in Figures 1 and 2. It is observed that the V_{OC} changes from 25.311 to 25.491 V. This saturation of V_{OC} leads to a reduction in efficiency under high-concentration conditions, as shown in Figure 3.

As shown in Figure 3, the efficiency η of the proposed VMJ cell exhibits a growth trend due to the logarithmic increase in the V_{OC} with increasing concentration. In fact, an efficiency value of about 26.4% at a concentration of 100 suns was achieved. The slight decrease in efficiency observed at relatively high concentrations, between 100 and 300 suns, can be attributed to the presence of series resistance. This effect becomes more predominant within the VMJ sub-cells. However, for concentrations exceeding 300 suns, the efficiency η decreases significantly. This is due to the relatively modest increase in the V_{OC}, as highlighted in both Figures 1 and 2. This means that this increase is negligible compared to the concentration increase, justifying the observed efficiency decrease at these high levels of light concentration. The next step is to study the impact of the fill factor on efficiency, as per in (4).

We need to revisit (4) considering the approximations made. It is noticeable that the efficiency η is proportional to the fill factor FF. This suggests that an increase in FF would lead to an increase in η. However, this correlation is not experimentally confirmed. In fact, Figure 4 presents a paradoxical phenomenon for concentrations (>300 suns): there is both an increase in FF from 0.7926 to 0.8389 and a decrease in the ideality factor from 24.751 to 17.272. Surprisingly, a higher FF does not necessarily guarantee better efficiency, as shown in Figure 3. It is therefore necessary to consider in (4) in its fundamental state for efficiency, which can be expressed as (13).

$$\eta = \frac{V_{OC} J_{SC} FF}{P_{optic}} \tag{13}$$

After conducting the previous study, we have established several crucial observations for high concentrations. Firstly, the V_{OC} reaches its saturation value. Subsequently, the fill factor FF experiences a slight increase, indicating a modest FF variation. Furthermore, it has been observed that the short-circuit current density J_{SC} does not significantly affect the efficiency. Taking these findings into account and referring to in (13), we can conclude that the efficiency decrease observed under these conditions can be attributed solely to the series resistance R_S, shunt resistance R_{sh}, or potentially other poorly understood physical phenomena.

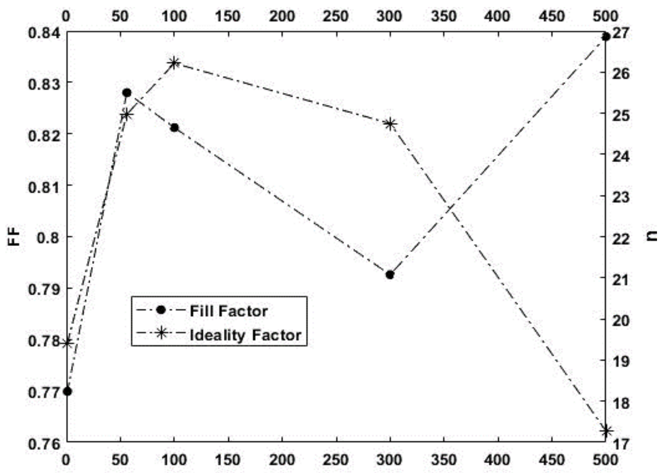

Figure 4. Variation of fill factor and ideality factor vs sun concentration

Figure 5 demonstrates that the series resistance R_S decreases from 0.7 to 0.023402 (Ω/cm²) as the light concentration goes from 1 to 50 suns. This rapid decrease in R_S for the VMJ cell is also a major reason for the initial increase in efficiency, rising from 19.419 to 24.977%. In the range of 50 to 300 suns, there is a slight variation in R_S, moving from 0.023402 to 0.0055467 (Ω/cm²). This stability in behavior further supports the explanation for the minimal, if not saturated, efficiency variation in this concentration range, from 24.977 to 24.751%, through the peak value of 26.213% at 100 suns, as shown in Figure 3. For concentrations exceeding 300 suns, the series resistance R_S becomes very low and equal to 0.0055467 Ω. In parallel, the shunt resistance R_{Sh} increases rapidly from 0.37327 to 1.42906 (Ω/cm²). This swift increase in R_{Sh} mirrors the rise of the fill factor FF, as illustrated in Figure 4.

Based on previous studies, it is evident that the rapid decline in VMJ cell efficiency at high concentrations (>300 suns) is mainly attributed to the saturation of J_{SC} and V_{OC}. However, it's equally possible that complex and less evident mechanisms play a role in this efficiency drop under high concentration. These mechanisms include recombination phenomena, the metallic contact between sub-cells, as well as temperature elevation under high concentration conditions.

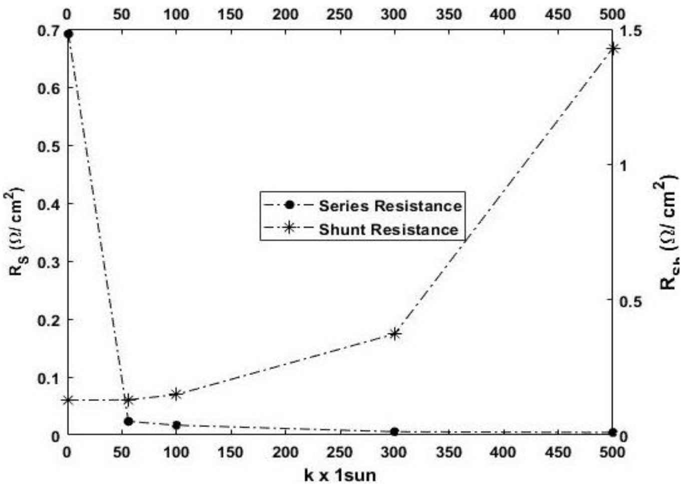

Figure 5. Variation of series and shunt resistances vs sun concentration

4. CONCLUSION

This publication introduces a theoretical study utilizing the least mean squares (LMS) method to extract the parameters of vertical parallel-junction silicon solar cells under concentrated illumination. Overall, the LMS method provides an efficient and succinct approach to extracting and expressing the parameters of the VMJ cell at both one sun and high solar illumination levels. Our study has illuminated the correlation between cell efficiency and levels of light concentration. Indeed, its efficiency rate evolves from around 19.419% at 1 sun to approximately 26.213% at 100 suns and subsequently decreases to around 17.272% at 500 suns. Similarly, we have demonstrated that the efficiency increases for concentrations below 300 suns are attributable to the elevation of voltage, which rises from approximately 19.147 V at 1 sun to around 25.311 V at 300 suns. This increase is not linked to current density, as it increases linearly with concentration. However, for concentration levels beyond 300 suns, both voltage and current begin to saturate, leading to a decrease in efficiency. We have considered that this efficiency decrease might not solely be attributed to resistance R_S and R_{Sh}, contrary to previous assumptions. In conclusion, vertical multi-junction silicon solar cells VMJ prove capable of delivering high voltages around 26 V, ensuring efficient operation even at intensities exceeding 500 suns AM1.5. Furthermore, these cells exhibit low series resistance at high concentrations, enhancing their appeal for high solar concentration applications.

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