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Impact of An Open Crack on The Output Characteristics of A Heterojunction Solar Cell

Amina Ennemri * , Halima Mazouz **‡ , Ali Khouzam ***, Pierre-Olivier Logerais ****‡

*Department of mechanical engineering, Faculty of technology, Laboratory of Energy, Mechanical and Engineering (LEMI), University of Boumerdès, 35 000 Boumerdès, Algeria.

**Fundamental and Applied Physics Laboratory (FUNDAPL), Faculty of Science, University Saad Dahleb, BP 270 Route Soumâa, Blida, Algeria.

***ICAM Grand-Paris Sud, Carré Sénart, 34 Points de Vue, 77127 Lieusaint, France.

****Univ Paris-Est Créteil, CERTES, 36 rue Georges Charpak, 77567 Lieusaint, France.

(a.ennemri@univ-boumerdes.dz, halima.mazouz@yahoo.fr, ali.khouzam@icam.fr, pierre-olivier.logerais@u-pec.fr)

‡ Corresponding Author; Fourth author, 36 rue Georges Charpak, 77567 Lieusaint, Tel: +33 1 64 13 46 86

Fax: +33 1 64 13 46 86, pierre-olivier.logerais@u-pec.fr

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Abstract- Photovoltaic modules experience various forms of degradation throughout their lifecycle, including during operation, transportation, installation and maintenance. Among common degradation modes, cracks are a significant factor contributing to the deterioration of photovoltaic panels. Indeed, the direct link between cracks and the efficiency loss of a photovoltaic module has not definitively been established to date. Therefore, the current study was focused on investigating the influence of the crack depth within a heterojunction solar cell using a finite element model. By conducting steady-state simulations of the PN junction, the study explored crack depths ranging from 0 to 5 µm. The results revealed a linear decrease in the short-circuit current with an increasing crack depth. Moreover, a substantial drop in the open-circuit voltage was observed for crack depths up to 0.25 µm. The overall efficiency of the solar cell was found to decrease markedly from 19.97% to 12.94% when the crack depth reached 5 µm. These findings highlight the importance of understanding and mitigating the impact of cracks on the performance of photovoltaic modules.

Keywords PN junction, heterojunction solar cell (HJ), open crack, modeling, output parameters.

1. Introduction

The solar cell is the most vulnerable component of a photovoltaic (PV) system, as it can be susceptible to cracking due to a combination of different manufacturing processes and operating conditions [1,2]. The presence of cracks in a photovoltaic module can have several adverse effects. Firstly, it can result in a gradual reduction in energy production over time. Additionally, cracks can cause various forms of degradation, including corrosion, delamination, hot spots, snail trails, or discoloration [3–6]. These cracks are predominantly visible on the surface of photovoltaic cells, particularly near the starting and ending points of the busbars, or along the busbars themselves [7,8]. These locations are common areas where cracks tend to develop and can be crucial points of concern for the overall structural integrity of the photovoltaic cell. Moreover, cracks can have a detrimental impact on the interconnecting ribbon, which is a vital component in the assembly of a solar PV module [9, 10]. Any failure or damage to the ribbon can have serious consequences, affecting not only the performance of the module and its efficiency but also its overall reliability [11]. As the interconnecting ribbon plays a crucial role in connecting individual solar cells to form the module, any compromise in its integrity can result in reduced electrical conductivity and power transmission efficiency. Hence, ensuring the proper functioning and structural integrity of the interconnecting ribbon is essential to maintaining the optimal performance of the entire photovoltaic module.

Researchers have employed a combination of experimental and modeling approaches to investigate microcracks in solar cells [2]. The primary objective of these studies has been to determine key characteristics such as the number, orientation, position and frequency of these microcracks. In more ways, these investigations aim to establish correlations between these identified parameters and the resulting power loss in the photovoltaic module [11,12].

When cracks are present in a solar cell, the parts that break off from the cell may not be entirely isolated [13]. Instead, there could be partial electrical connections. However, the series resistance across these cracks can vary, and this variation depends on two main factors [14]. Firstly, the special gap between the disconnected cell parts plays an important role in determining the electrical continuity or discontinuity of the affected parts [10]. A smaller gap might still allow some level of electrical connection, while a larger gap could lead to a more substantial loss of electrical continuity. Secondly, the extent of deformation the PV module undergoes over multiple cycles, such as thermal expansions and contractions, can also affect the series resistance across the cracks [13]. These mechanical stresses can cause changes in the dimensions or positions of the cracks, leading to fluctuations in their electrical properties [15]. As a result of these variations in series resistance, the electrical performance of the solar cell is impacted, which, in turn, affects the overall efficiency and power output of the PV module. Nevertheless, when a cell part is fully isolated due to a crack, the decrease in the current is directly proportional to the disconnected area [16]. In other words, the larger the area that is entirely separated and electrically isolated from the rest of the solar cell, the greater the reduction in the current flow is through that specific section.

The orientation of a crack becomes significant when dealing with microcracks, as orientation changes directly the impact on the output efficiency [17]. On the other hand, in the case of deep cracks, the output efficiency varies with the size of the crack. As the crack size increases, there is a proportional drop in the power efficiency. For microcracks, orientation matters, while for deep cracks, size is the determining factor for power efficiency. This relationship is an important consideration because it highlights the direct effect of the crack size and the extent on the electrical performance of the solar cell [15]. Larger isolated areas result in more substantial current reductions, which in turn decrease the overall efficiency of the PV module.

According to the research conducted by Kajari-Schröder et al., the presence of a single crack with a parallel orientation in a silicon solar cell was associated with a power reduction of around 25% [7]. On the other hand, Subrahmanyan et al., observed the appearance of cracks at the interconnection of soldering joints when subjected to thermal cycles. This phenomenon led to an increase in the series resistance, consequently causing a reduction in both the fill factor and the power generated by the solar cells [18]. What's more, a simulation study carried out by Morlier et al., based on field data, estimated the power loss of multicrystalline silicon modules ranging from 6 to 22% in the presence of cracks [19]. Furthermore, in another research effort, a multi-physics and multi-scale numerical approach demonstrated that the evolution of microcracks in polycrystalline silicon solar cells had a considerable impact on their electrical responses causing notable power losses [16]. Specifically, it was reported that the fill factor decreased from 65% to 15% for a module affected by microcracks. These findings emphasize the substantial consequences that cracks can have on the performance and efficiency of solar cell technologies, underscoring the need for effective measurements to address and mitigate the effects of macrocracks in PV modules.

In the present study, the focus is on a specific type of solar cell known as a heterojunction solar cell (HJ) a-Si/c-Si. This technology was chosen due to its inherent advantages and improved temperature coefficients in comparison to traditional homojunction c-Si cells, making it a promising and appealing option [20,21]. Heterojunction solar cells offer a unique combination of benefits, including the high performance associated with crystalline and the advantageous low heat balance resulting from the utilization of a thin amorphous silicon layer. These attributes have sparked considerable interest in the field of photovoltaic solar cells, leading to extensive research efforts to further explore and optimize HJ solar cell technology [22,23]. While photovoltaic cell cracking has been addressed to some extent in crystalline silicon homojunction photovoltaic cells, its impact on the performance of heterojunction photovoltaic cells remains relatively unknown.

The main objective of the current study is to shed light on the effects of cracks specifically in the context of heterojunction photovoltaic cells and on the relationship between open crack presence, varying crack thicknesses, and their influence on the output parameters of the heterojunction (HJ) solar cell composed of a-Si (p)/c-Si (n) under the AM 1.5 spectrum. To achieve this objective, a 2D finite element model was employed to simulate the degraded characteristics and to analyze the decline in the electrical output parameters arising from the presence of the crack. By exploring the impact of an open crack on the electrical performance of the heterojunction solar cell, this research aims to contribute valuable insights into the reliability and efficiency of HJ solar cell technologies. These findings could be instrumental in developing strategies to mitigate the effects of cracks, ultimately advancing the practical applications of this promising photovoltaic technology.

2. Model of the heterojunction solar cell

2.1. Approach

This section presents the details of the model used in the simulation, including the structure, mesh, equations, data, and boundary conditions. The model represents a two-dimensional PN junction with the incorporation of an open crack. The structure of the model is designed to reproduce the behavior of the heterojunction solar cell, comprising a-Si (p) and c-Si (n) layers.

The meshing technique is applied to discretize the two-dimensional domain, allowing for finer resolution and accurate representation of the crack.

The equations governing the behavior of the PN junction, such as the drift-diffusion equations, continuity equations, and Poisson's equation, are incorporated into the model to describe the electrical and transport phenomena occurring within the solar cell.

The data used in the simulation include material properties, carrier mobilities, and recombination rates of both a-Si and c-Si layers, ensuring a realistic representation of the semiconductor behavior.

The boundary conditions were defined to emulate the operating conditions of the solar cell under the AM 1.5 spectrum.

Furthermore, the presence of an open crack is explicitly considered within the two-dimensional representation of the PN junction. This allows for the examination of the impact of the crack on the electrical performance of the heterojunction solar cell and to provide insights into its influence on the output parameters.

Overall, the model is a valuable tool for studying the behavior of the heterojunction solar cell in the presence of an open crack, enabling a comprehensive analysis of the effects of the crack and aiding in the development of strategies to improve the reliability and efficiency of HJ solar cell technologies.

2.2. Structure

Figure 1 depicts the structure of the a-Si/c-Si solar cell under investigation, featuring a thin film of highly doped amorphous silicon (a-Si p) and a moderately doped monocrystalline silicon wafer (c-Si n). The absorber layer c-Si (n) has a thickness of 300 µm, while the emitter layer a-Si (p) is 2 µm thick. The cell width is 5 µm.

To study the impact of cracks on the behavior of the solar cell, a finite element model of the PN junction was developed for both a healthy junction and a junction with an open crack. The open crack has a width of 1 µm, and its depth varies from 0 to 5 µm.

This modeling approach enables the assessment of two scenarios: one where the crack is solely within the emitter layer and another where it extends across both the emitter and the base layers. By considering the modified depletion region following from the presence of the crack, the simulation accounts for the different positions of the crack and their potential influence on the electrical characteristics of the solar cell.

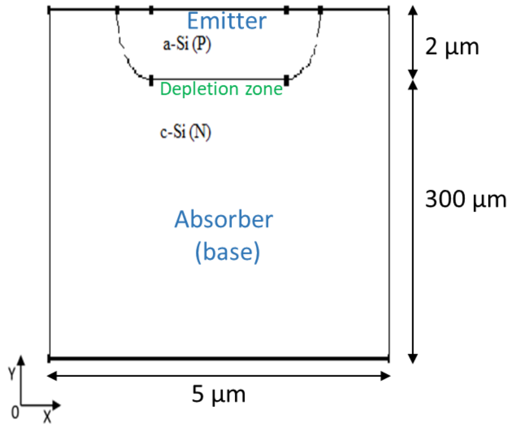


Fig. 1. Structure of the simulated heterojunction solar cell.

2.3. Mesh

Figure 2 displays the generated mesh of the PN junction for both a healthy solar cell and a PV cell with an open crack. The simulation faces a substantial challenge owing to the wide variation in carrier concentrations, necessitating a careful approach to numerically solving the semiconductor equations.

For this reason, we carefully generated a denser mesh around the depletion region, at the anode and cathode regions. By using a finer mesh in these critical areas, we ensured better accuracy and precision in capturing the electrical behavior of the semiconductor.

The maximum element size in the mesh was set to 1×10^{-7} m^2 and 3684 elements were taken to discretize the domain. This mesh configuration allowed for a more detailed representation of the heterojunction solar cell, enabling a comprehensive analysis of the effects of an open crack on its electrical performance.

With this carefully generated mesh, the simulation can effectively model the intricate behavior of carrier concentrations and accurately evaluate the impact of the crack on the output parameters of the solar cell, providing valuable insights into its reliability and efficiency under varying conditions.

2.4. Equations

The charge carrier continuity and the space-charge effect are solved by a coupled resolution based on Poisson's equation (1), the equation of continuity for electrons (2) and for holes (3) [23]. The following equations were applied for the x direction:

$$-\nabla.(\varepsilon.\nabla\psi) = q.(p - n + N) \qquad (1)$$

$$\frac{dJ_n}{dx} = -q.(G - R) \qquad (2)$$

$$\frac{dJ_p}{dx} = q.(G - R) \qquad (3)$$

where for equation (1), Ψ is the electrostatic potential, n and p are the electron and the hole concentrations respectively; ε is the dielectric permittivity; q is the elementary charge; N represents the fixed charge associated with the ionized donors.

On the other hand, in equations (2) and (3), J_n and J_p are the electron and hole current densities; G is the carrier generation by optical absorption and R is the recombination rate. In silicon, there are recombination via defects following a Shockley-Read-Hall (SRH) mechanism and direct band-to-band recombination following an Auger mechanism.

For the Auger recombination, the minority carrier lifetime is:

$$\tau_{Auger(n/p)} = \frac{1}{C(p_0+n)^2} \tag{4}$$

with C is the Auger recombination coefficient, p_0 is the initial hole concentrations and n is the electron concentrations.

As for the Shockley Read-Hall recombination, the minority carrier lifetime is:

$$\tau_{SRH} = \frac{n}{R_{SRH}^{Volume}} \tag{5}$$

where R_{SRH}^{Volume} represents the SRH recombination in volume:

$$R_{SRH}^{Volume} = \frac{np-n_i^2}{\tau_p(n+n_t)+\tau_n(p+p_t)} \tag{6}$$

Due to cracking, the silicon surface contains defects. The silicon surface may also contain a quantity of adsorbed impurities. These impurities/surface defects generate Shockley-Read-Hall recombination on the silicon surface. By replacing volume quantities with the surface quantities in the SRH recombination, a lifetime relationship for the surface recombination is obtained:

$$\tau_S = \frac{w}{2s} + \frac{1}{D}\left(\frac{w}{\pi}\right)^2 \tag{7}$$

where s is solar cell surface, D is the surface defect density and w is the sample thickness.

In order to bring these different mechanisms together in a single lifetime value, we used the concept of effective lifetime:

$$\frac{1}{\tau_{(n/p)}} = \frac{1}{\tau_{SRH(n/p)}} + \frac{1}{\tau_{Auger(n/p)}} + \frac{2s}{w} \tag{8}$$

The generation of the free carriers is an optical generation G given by:

$$G = (1-r).\alpha(\lambda).\phi(\lambda)\exp(-\alpha(\lambda).x) \tag{9}$$

where r is the reflectivity of the front contact, $\phi(\lambda)$ is the flux of incident photons of wavelength λ, and $\alpha(\lambda)$ is the spectral absorption coefficient [23].

2.5. Physical Data

The material properties used in the model are detailed in Table 1.

2.6. Boundary Conditions

To solve the governing equations (1)-(3) in the finite element model, certain boundary conditions were imposed to accurately simulate the behavior of the heterojunction solar cell. These boundary conditions ensured the continuity and appropriate values of electric potential, electric field, and carrier densities at different interfaces and regions within the cell.

At interface (ii), representing the interface between the two semiconductor materials, we assumed the continuity of electric potential and electric field.

Far from the active zones of the component, boundary conditions were set to zero for the normal electric field component and carrier densities. This assumption permits a realistic representation of the behavior of the cell in the regions which don't actively contribute to the electrical output.

For the electrical contacts, boundary (i) touching the metal was set to have an electric potential of 0.5 V, while boundary (iii) at the back was set to 0 V. Infinite recombination velocity was assumed on these surfaces, implying that any charge carriers reaching these boundaries are instantaneously recombined.

Regarding the side walls (boundary (iv)), a symmetrical condition was specified with zero charges. This decision was made because the model only represents a portion of the full PV cell, and the absence of any charge on these side walls avoids introducing unintended effects.

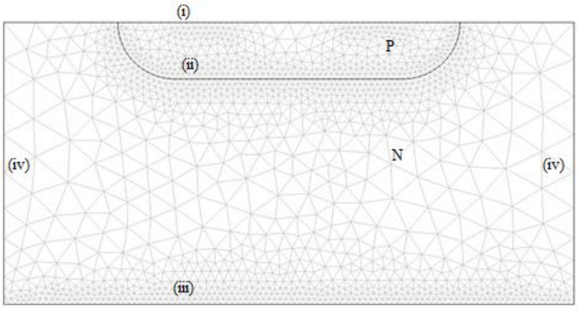
By carefully setting these boundary conditions, the finite element model was able to accurately simulate the electrical behavior of the heterojunction solar cell, providing meaningful insights into the impact of the open crack on the performance of the PV cell.

In addition to the reference case (a) of a junction without cracking, two other scenarios were considered in the numerical simulations:

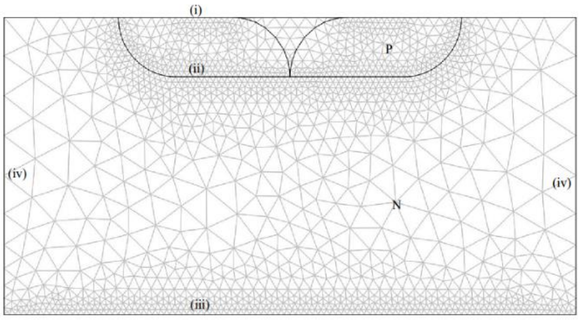
- Case (b): the depth of the crack was fixed between 0 and 2 µm, meaning that the cracking occurred only in the emitter a-Si layer;
- Case (c): the depth of the crack exceeded 2 µm, implying cracking in both layers, i.e., in both the emitter a-Si (p) and the base c-Si (n) layers of the solar cell.

For both Case (b) and Case (c), the electric potential at the boundary (i) of the crack was set to 0.5 V. This boundary condition reflects the presence of electrical contacts or metal interconnections at the surface of the crack.

The depth of the crack was arbitrarily chosen to range up to 5 µm for the numerical simulations. This choice allowed for a comprehensive investigation of the impact of the crack on the electrical output parameters of the heterojunction solar cell across a consistent range of crack depths, providing a deeper comprehension of how the crack depth influences the performance of the PV cell.



a) Healthy cell



b) Cell with an open crack of 2 µm depth

Fig. 2. Mesh of the intact and cracked heterojunction cell.

Table 1. Material properties [14].

Parameters	a-Si(p)	c-Si(n)
Thickness (µm)	2	300
Band gap (eV)	1.72	1.124
Auger recombination coefficient for electrons ($cm^6.s^{-1}$)	0	2.2×10^{-31}
Auger recombination coefficient for holes ($cm^6.s^{-1}$)	0	9.9×10^{-32}
Electron mobility ($cm^2.V^{-1}.s^{-1}$)	25	1040
Hole mobility ($cm^2.V^{-1}.s^{-1}$)	5	412
Dielectric constant	11.9	11.9
Surface recombination velocity	6×10^3	6×10^3

3. Calculations

3.1. Boundary Conditions

In this study, numerical simulations of the silicon solar cell were conducted under Standard Test Conditions, which involve exposure to an atmosphere with Air Mass 1.5 (AM1.5) solar spectrum. AM1.5 spectrum with an integral power density of 1000 W.m^{-2} and a 25°C cell temperature were set.

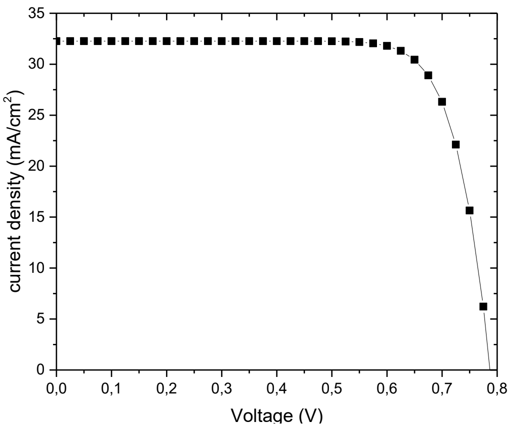


Fig. 3. J(V) characteristics of healthy a-Si(p)/c-Si(n) junction.

To incorporate the solar spectrum into the simulations, an input database was utilized, providing the necessary spectral information for the AM1.5 conditions. The simulations were carried out under steady-state conditions, representing a situation where the system reaches equilibrium with a constant input for the solar irradiance.

The numerical analysis was performed using Lagrange quadratic elements with an integration order of 4 and a constraint order of 2. These elements are part of the finite element method, enabling accurate and efficient numerical approximations of the physical behavior of the solar cell.

The finite-element resolution was executed using COMSOL Multiphysics software which is a powerful and widely used simulation tool capable of handling both the electrostatic and diffusion modules relevant to the behavior of the heterojunction solar cell [24]. This software package provided the necessary computational capabilities to model accurately the complex interactions and processes occurring within the solar cell.

3.2. Calculations of the Output Parameters

The equation for the short-circuit current density can be approximated as:

$$J_{sc} = qG(L_n + L_n) \tag{9}$$

where L_n and L_n are the electron and hole diffusion lengths respectively.

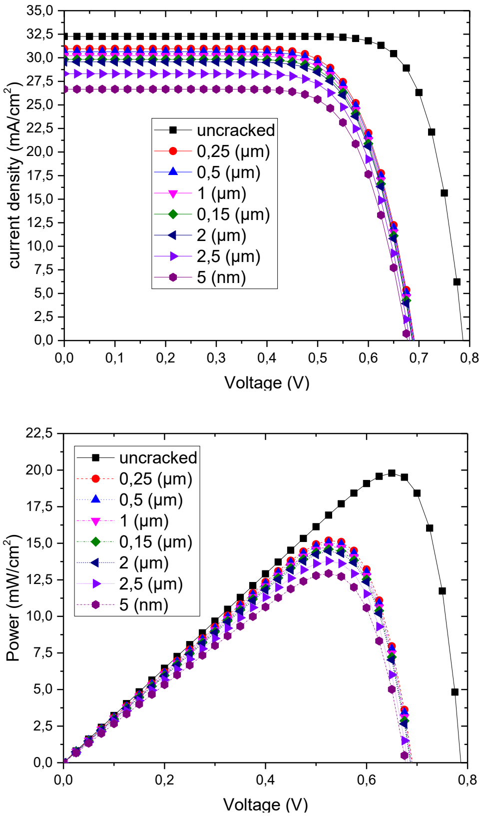


Fig. 4. Evolution of the (a) current density–voltage *J(V)* and (b) power–voltage P(V) characteristics according to the crack depths.

4. Model of the Heterojunction Solar Cell

4.1. Analysis of the Electrical Characteristics of the Healthy Solar Cell

The electrical characteristics of the healthy solar cell were analyzed through a numerical simulation as a reference case, where no crack was present. The J(V) characteristic, representing the current-voltage relationship of the basic a-Si(p)/c-Si(n) heterojunction cell, was obtained under the standard AM1.5 spectrum, as shown in Figure 3.

From this J(V) characteristic, the following output parameters were extracted:

- The density of the short-circuit current, J_{sc} was found to be 32.27 mA/cm^{-2}.
- The open-circuit voltage, V_{oc}, was calculated to be 0.7867 V.
- The fill factor, FF, was calculated to be 77.93%.
- The efficiency of the solar cell, denoted by η, was determined to be 19.79%.

These values represent the electrical performance of the healthy solar cell under the given simulation conditions. The absence of a crack allowed for the determination of the baseline characteristics, serving as a reference for comparison with the deteriorated solar cell containing an open crack.

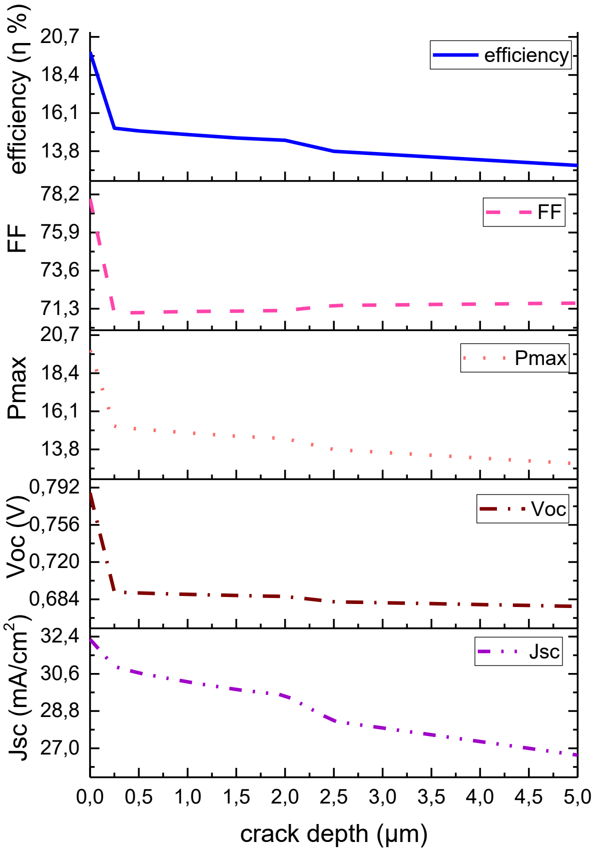


Fig. 5. Effects of the crack depth on the performance of the heterojunction.

Table 2. Output parameters of the solar cell with different crack depths.

Crack depth (µm)	0	0.25	0.5	1.0	1.5	2.0	2.5	5.0
J_{sc} (mA/cm^2)	32.27	30.95	30.64	30.21	29.84	29.57	28.31	26.67
V_{co} (V)	0.787	0.691	0.690	0.689	0.688	0.687	0.681	0.677
FF	77.93	71.02	71.06	71.13	71.15	71.19	71.49	71.64
η%	19.79	15.19	15.03	14.80	14.60	14.46	13.79	12.94
Reduction of η%	0	23.23	24.06	25.20	26.22	26.94	30.29	34.62

4.2. Analysis of the Electrical Characteristics of the Cracked Solar Cell

The electrical characteristics and output parameters of the heterojunction solar cell were analyzed with the presence of an open crack at different depths. A range of distinctive crack depths was considered in the simulation. Additionally, the characteristics of the uncracked cell were calculated for comparison.

Figure 4 illustrates the evolution of the current density and of the power output versus voltage for various crack depths. Clearly, a deterioration in the output parameters is observed with increasing crack depth.

Specifically, the short-circuit current density (J_{sc}) exhibits a noticeable decrease as the crack depth increases. On the other hand, the open-circuit voltage (V_{oc}) remains approximately constant but experiences a reduction compared to the healthy solar cell. This indicates that the presence of a crack induces a loss in the open-circuit voltage, impacting the electrical performance of the solar cell.

To quantitatively evaluate the impact of the crack, the reductions in J_{sc}, V_{oc} and the power conversion efficiency (η) were plotted against the crack depth in Figure 5. Furthermore, the relative reduction in the efficiency was calculated using the following expression:

$$Relative\ reduction\ in\ Efficiency\ (\%) = \frac{\eta_0 - \eta_c}{\eta_0} \times 100 \quad (10)$$

where η_0 is the efficiency of the cell without a crack and η_c is the efficiency of the cracked cell.

The values obtained from the expression were summarized in Table II, providing a clear representation of the decline in the efficiency with respect to the depth of the open crack.

The study reveals a clear impact of the open crack on the efficiency of the heterojunction solar cell. For the smallest crack depth of 0.5 μm, the efficiency decreased from 19.79% to 15.19%, corresponding to a reduction of 23.23%. As the crack depth increased to the deepest (5 μm), the efficiency further dropped to 12.94%, ensuing in a substantial 34.62% reduction.

This decrease in efficiency can be attributed to several factors. In the presence of a crack, there are inactive or less active zones within the solar cell, reducing the available carriers for the generation of electrical current. Besides, the crack can obstruct the path of incident light, resulting in a lower amount of light energy being converted into electrical current.

As a consequence, the electrical performance of the solar cell is compromised, engendering a reduction in both the short-circuit current density and the open-circuit voltage. The combination of these effects contributes to the observed decline in efficiency as the crack depth increases.

These findings emphasize the significance of addressing crack-related issues in heterojunction solar cells to maintain their efficiency and ensure their optimal performance over time. By knowning the implications of cracks on the electrical characteristics of the solar cell, appropriate measures can be implemented to improve the reliability and efficiency of photovoltaic systems in practical applications.

The simulated output results presented in Figure 5 exhibit noteworthy trends. There is a pronounced variation in the output parameters for crack depths ranging from 0 to 0.25 μm. Subsequently, for crack depths between 0.25 and 2 μm, the output parameters display linear degradations, with the following slopes: -0.0417 %.μm^{-1} for efficiency (η), -0.00023 V.μm^{-1} for open-circuit (V_{oc}) and -0.0788 mA.cm^{-2}.μm^{-1} for J_{sc}. Linear degradations of the output power according to the size of the crack for silicon-based solar cells were also found in the study of [15].

The decrease in output parameters between 2 and 2.5 μm is also consistent, but more significant owing to the influence of the depletion region. Beyond 2.5 μm depth, the slopes continue to exhibit a consistent pattern with values of -0.034 %.μm^{-1} for η, -0.00016 V.μm^{-1} for V_{oc} and -0.0656 mA.cm^{-2}.μm^{-} for J_{sc}.

The observed degradations in the output parameters of the heterojunction solar cell can be justified through experimental analysis of cracks in silicon-based cells, both monocrystalline and polycrystalline, as cited in references [25,26]. These experimental studies provide evidence to show how cracks can negatively impact the electrical characteristics and performance of solar cells. In the case of heterojunction (HJ) cells, cracks can give rise to poor contact between the busbar and the fingers, inducing increased contact resistance. This poor contact impedes the smooth flow of current within the cell, resulting in losses in the electrical performance.

Larger cracks in the system can have a profound impact on the overall output power, causing a substantial decrease which can be of nearly 60% [27]. These cracks can hinder the efficiency and performance of the system, leading to significant energy losses. Also, as the surface of the crack expands, there is a corresponding rise in the temperature of the cell [27]. Furthermore, the presence of cracks can cause a raise in the series resistance, as reported in reference [28]. As previously seen, series resistance is a critical parameter affecting the overall efficiency of a solar cell, and any increase in the series resistance implies a reduction in the current flow within the cell [13,14].

More, cracks can contribute to a limited extent to the reduction of the open-circuit voltage (V_{oc}), as noted in [29,30]. This reduction in V_{oc} is attributed to the interruption of the current path caused by the crack, ending in less efficient separation of charge carriers, particularly at the junctions.

These observations highlight the complex relationship between the crack depth and the consequent changes in the electrical output parameters of the heterojunction solar cell.

Indeed, the findings of this study have major implications for the management of photovoltaic installations and smart grids. The knowledge gained from analyzing the impact of cracks on the performance of heterojunction solar cells can be leveraged in various ways to enhance the efficiency and reliability of solar energy generation [31].

Foremost, the insights supplied by this research can aid in the development of efficient maintenance strategies for photovoltaic installations. By comprehending the detrimental effects of cracks on the electrical characteristics of solar cells, operators and maintenance teams can implement proactive measures to detect and address crack-related issues promptly [32–35]. This early fault detection can help prevent further degradation in performance, optimize the operation of solar installations, and extend the lifespan of the solar cells. As a consequence, energy yield from solar installations can be maximized, in order to achieve greater energy generation and cost-effectiveness.

Secondly, the results of this study can contribute to the design and improvement of solar cell manufacturing processes [9]. By identifying the factors that contribute to the crack-induced degradation of the performance, manufacturers can implement enhanced quality control measures to reduce the occurrence of cracks during cell production [36,37]. Indeed, this grasp can guide the development of improved materials and manufacturing techniques to enhance the durability and reliability of solar cells, making them more resilient to potential crack formation during their lifetime.

The investigation of the relationship between the crack depth and the resulting decrease in electrical output parameters is a crucial aspect of this study. The knowledge gained from this exploration can prove to be highly valuable to system designers and network operators involved in the management and optimization of photovoltaic installations.

By mastering how crack depth impacts the electrical performance of heterojunction solar cells, system designers can develop better strategies for cell design and module assembly. They can consider factors that contribute to crack formation and implement measures to minimize crack occurrences or mitigate their effects on cell performance. This knowledge can be useful for the development of more robust and reliable solar cell designs, improving the overall efficiency and longevity of solar installations.

For network operators responsible for managing large-scale solar arrays, the insights of this study can inform the implementation of preventive measures [38]. Early fault detection systems can be employed to continuously monitor the performance of solar cells and identify any degradation caused by cracks or other issues [39]. By promptly identifying and addressing such performance degradation, network operators can take proactive actions to prevent further damage, optimize energy output, and ensure the smooth functioning of solar power plants.

5. Conclusion

In conclusion, this study focused on the impact of an open crack on the performance of a heterojunction (HJ) solar cell composed of a-Si(p)/c-Si(n) under the AM 1.5 spectrum. Through the utilization of a 2D finite element model, the presence of cracks with varying thicknesses was simulated to analyze their influence on the electrical output parameters of the solar cell.

The simulation results clearly demonstrate that the presence of a crack leads to a decrease in the output parameters of the HJ solar cell. Initially, the PV cell exhibited an efficiency of 19.79%, an open-circuit voltage (V_{oc}) of 0.7867 V, and a density current (J_{sc}) of 32.27 mA.cm^{-2}. However, for a cracked cell with a depth of 5 µm, the efficiency reduced to 12.94%, V_{oc} decreased to 0.6772 V, and J_{sc} declined to 26.76 mA.cm^{-2}.

The relationship between the decline in the electrical output parameters and the depth of the crack exhibited a proportional behavior beyond a depth of 0.25 µm. This suggests that as the crack depth increases, the degradation of the performance of the solar cell becomes more pronounced.

The findings of this study have wide-ranging implications for the solar energy industry. The insights gained from examining the impact of cracks on heterojunction solar cells can drive more effective decision-making and strategic planning in various aspects of the industry.

Firstly, the knowledge gained from this study can guide the development of preventive measures to mitigate the negative effects of cracks on solar cell performance. Having awareness of the factors contributing to crack-induced degradation, system designers and manufacturers can implement design improvements and quality control measures to reduce crack occurrences during cell production. This, in turn, may enhance the overall performance and durability of photovoltaic systems.

Secondly, network operators responsible for managing solar power plants can leverage this knowledge to implement early fault detection systems. By promptly identifying and addressing crack-related issues, operators can prevent further performance degradation, optimize energy output, and ensure the smooth functioning of solar installations.

Ultimately, the take-up of such preventive measures can contribute to the widespread adoption of solar energy as a clean and sustainable power source. It fosters the development of more efficient and reliable photovoltaic systems, making solar energy an increasingly attractive and viable option for meeting the world's energy needs.

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