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Study of the Effect of Carbon-60 (C-60 Fullerene) on the Photovoltaic Properties and Efficiency of Solar Cells

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دراسة تأثير الكربون 60 (C-60 Fullerene) على الخصائص الكهروضوئية وكفاءة الخلايا الشمسية

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Abstract:
This study aims to investigate the effect of Carbon-60 (C-60 Fullerene) on the photovoltaic performance of solar cells by analyzing the current–voltage (I–V) characteristics of three different samples. The performance was evaluated using key solar-cell parameters, including open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}), fill factor (FF), and power conversion efficiency (η). The results showed a gradual improvement in efficiency from 0.182% to 0.504% with the incorporation of C-60, indicating its effective role in enhancing electron transport and reducing charge recombination losses. The fill factor remained constant at 0.89, reflecting good electrical characteristics of the devices. The study confirms that the use of C-60 contributes significantly to improving the photovoltaic performance of solar cells and enhancing their ability to convert solar energy into electrical energy.

Keywords: Carbon-60 (C-60), Fullerene, Solar Cells, Photovoltaic Properties, Current–Voltage Characteristics, Power Conversion Efficiency, Electron Transport.

الملخص
يهدف هذا البحث إلى دراسة تأثير مادة الكربون 60 (C-60 Fullerene) على الأداء الكهروضوئي للخلايا الشمسية من خلال تحليل خصائص التيار–الجهد (I–V) لثلاث عينات مختلفة. تم تقييم الأداء باستخدام معايير الخلية الشمسية الأساسية مثل جهد الدائرة المفتوحة (V_{OC})، وكثافة تيار القصر (J_{SC})، وعامل الامتلاء (FF)، وكفاءة التحويل (η). أظهرت النتائج تحسنًا تدريجيًا في الكفاءة من 0.182% إلى 0.504% مع زيادة تأثير طبقة C-60 ، مما يدل على دورها الفعال في تعزيز نقل الإلكترونات وتقليل فقد الشحنات الناتج عن إعادة الاتحاد. كما أظهرت النتائج ثبات عامل الامتلاء عند قيمة 0.89، مما يشير إلى جودة الخصائص الكهربائية للخلية. تؤكد الدراسة أن استخدام C-60 يسهم في تحسين الأداء الكهروضوئي للخلايا الشمسية وزيادة قدرتها على تحويل الطاقة الشمسية إلى طاقة كهربائية.

الكلمات المفتاحية: الكربون 60(C-60) ، الفولورين، الخلايا الشمسية، الخصائص الكهروضوئية، منحنى التيار–الجهد، كفاءة التحويل، نقل الإلكترونات.

1. Introduction

Solar energy is considered one of the most important renewable energy sources due to the increasing global demand for clean and sustainable energy [1,2]. Continuous efforts are being made to improve the efficiency of solar cells through the development of advanced materials with superior electronic and optical properties [3,4]. Carbon-60 (C-60), commonly known as Fullerene, is one of the most widely studied carbon nanomaterials because of its excellent electron-accepting and transport capabilities [5,6]. Previous studies have demonstrated that incorporating C-60 into solar-cell structures enhances charge separation and reduces recombination losses, leading to improved electrical performance and higher conversion efficiencies [7–9]. Changes in the physical properties revealed a tendency toward increased structural compactness and reduced free volume, indicating improved packing within the material network [16]. The quality of an imaging system is significantly affected by its operating physical parameters, where appropriate adjustment of these parameters contributes to obtaining clearer images and improving diagnostic performance [17]. Optical properties provide important information about the interaction between materials and electromagnetic radiation, helping to understand their electronic structure and potential technological applications [18]. "The study of optical properties of solids has a vital role in revealing the band structure of materials for use in optical and electronic devices. These properties are highly dependent on the chemical composition of the host material."[19]. "Photoelectric properties refer to a material's capacity to absorb incident electromagnetic radiation (such as photons) and convert it into electrical energy, either by emitting electrons or altering its internal electrical conductivity."[21].

2. Theoretical Background

2.1. Carbon-60 (C-60)

Carbon-60 is a nanostructured allotrope of carbon consisting of 60 carbon atoms arranged in a spherical cage-like structure resembling a soccer ball [5,10]. It possesses unique electronic and optical properties that make it suitable for applications in photovoltaic and electronic devices [6,11].

2.2. Solar Cells

Solar cells are devices that convert sunlight directly into electrical energy through the photovoltaic effect [1,12]. Their efficiency depends on light absorption, charge-carrier generation, charge separation, and charge transport to the electrodes [3,13]. "An increase in temperature raises the kinetic energy and velocity of gas molecules, causing a sinusoidal oscillatory behavior (according to Maxwell's distribution) that directly affects their spectral characteristics, varying the spectrum line width, area, and wavelength either proportionally or inversely depending on the nature of the target gas."[20].

2.3. Role of C-60 in Solar Cells

C_{60} acts as an efficient electron acceptor, facilitating the transport of photogenerated electrons and reducing electron–hole recombination [7,8]. This leads to improved charge extraction and enhanced photovoltaic performance [9,14].

2.4. Photovoltaic Parameters

The performance of solar cells is commonly evaluated using several key photovoltaic parameters that describe the electrical characteristics and energy-conversion capability of the device [12,13]. These parameters provide important information about charge generation, transport, and collection within the solar cell.

2.4.1. Open-Circuit Voltage (V_{OC}): The maximum voltage generated by the solar cell when no external load is connected. It is strongly influenced by the material properties, energy-band structure, and recombination mechanisms within the device [12].

2.4.2. Short-Circuit Current (I_{SC}): The current produced when the terminals of the solar cell are directly connected. It reflects the number of photogenerated charge carriers collected by the electrodes and is closely related to light absorption efficiency [12,13].

2.4.3. Short-Circuit Current Density (J_{SC}): The short-circuit current normalized to the active area of the solar cell. This parameter allows accurate comparison between devices of different sizes and is widely used in photovoltaic characterization [13].

2.4.4. Fill Factor (FF): The fill factor represents the quality of the current–voltage (I–V) characteristics of a solar cell. It is defined as the ratio between the maximum obtainable power and the product of V_{OC} and I_{SC}. Higher FF values indicate lower internal losses and better charge transport within the device [15].

2.4.4. Power Conversion Efficiency (η): The power conversion efficiency is the most important parameter used to evaluate solar-cell performance. It represents the percentage of incident solar energy converted into usable electrical power. The efficiency depends on V_{OC}, I_{SC}, and FF, as well as the optical and electrical properties of the active materials [3,13,15].

The incorporation of C-60 into solar-cell structures can significantly influence these photovoltaic parameters by enhancing electron transport, reducing charge-carrier recombination, and improving charge extraction efficiency.

Consequently, improvements in V_{OC}, I_{SC}, FF, and overall power conversion efficiency are often observed in C-60-based photovoltaic devices [7–9,14].

3. Research Problem

Many solar cells suffer from limited efficiency due to charge recombination losses and inefficient electron transport within the active layers. Therefore, there is a need to investigate the effect of Carbon-60 (C-60) on improving charge transport, reducing electrical losses, and enhancing the overall efficiency of solar cells.

4. Research Objectives

1-To study the effect of Carbon-60 on the photovoltaic properties of solar cells.
2-To evaluate changes in V_{OC}, J_{SC}, FF, and conversion efficiency.
3-To investigate the role of C-60 in improving electron transport and reducing recombination losses.
4-To identify the best-performing sample based on photovoltaic parameters.
5-To analyze the relationship between electrical characteristics and power conversion efficiency.

5. Materials

1-Carbon-60 (C-60 Fullerene)
2-Conductive glass substrates
3-Active-layer materials for solar-cell fabrication
4-Metallic electrodes
5-Solvents and cleaning chemicals

6. Equipment

1.I–V Measurement System
2-Solar Simulator
3-DC Power Supply
4-Digital Multimeter
5-Computer for data acquisition and analysis
6-Thin-film deposition equipment

7. Experimental Method

1-Clean and prepare the conductive substrates.
2-Deposit the active layers of the solar cell.
3-Introduce the C_{60} layer under controlled preparation conditions.
4-Attach the electrical electrodes.
5-Expose the solar cells to standard simulated solar irradiation.
6-Measure the current–voltage (I–V) characteristics.
7-Calculate V_{OC}, J_{SC}, FF, and efficiency values.
8-Compare the obtained results among the different samples.

8. Results and Discussion

The performance of the fabricated solar cells was evaluated through the analysis of current–voltage (I–V) characteristics and the extraction of key photovoltaic parameters. The results revealed a gradual improvement in voltage, current density, and conversion efficiency with the incorporation of Carbon-60, demonstrating its effectiveness in enhancing charge transport and reducing energy losses within the solar cell.

Table (1) shows the relationship between current and voltage for the first sample

Voltage (V)	Current (mA)
0.018	53
0.025	53
0.04	53
0.05	53
0.09	53
0.116	43.28
0.12	0
0.018	53

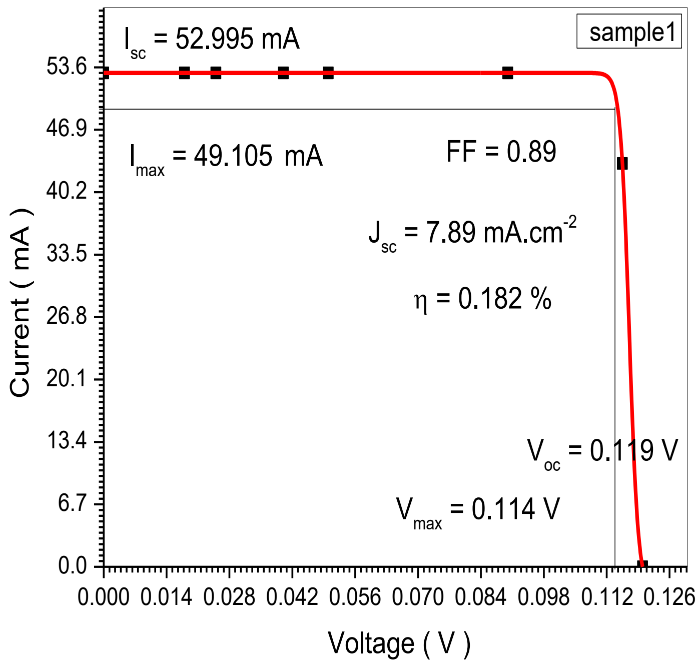

Figure (1) the relationship between current and voltage for the first sample.

The I–V characteristics obtained for the solar cells incorporating **C-60 (Fullerene Carbon-60)** exhibit typical photovoltaic behavior, as shown by the nearly rectangular shape of the curve and the sharp drop in current near the open-circuit voltage region. This behavior indicates efficient charge generation and collection within the device.

The gradual increase in conversion efficiency from **0.182%** to **0.504%** suggests that the incorporation of C-60 contributed positively to the photovoltaic performance. Fullerene C-60 is widely recognized as an excellent electron acceptor and transport material due to its high electron mobility and favorable energy levels. Consequently, the presence of C-60 enhances charge separation and facilitates electron transport, reducing charge recombination losses inside the solar cell.

The increase in $\mathbf{V_{OC}}$ and $\mathbf{J_{SC}}$ values observed in the third sample indicates improved carrier extraction and more effective utilization of the incident light. The higher current density may be attributed to enhanced light harvesting and efficient electron collection provided by the C-60 layer. Similarly, the increase in the open-circuit voltage suggests a reduction in recombination processes and improved interfacial charge transfer.

The fill factor (**FF = 0.89**) remained relatively high and constant for all samples, indicating good diode quality and low internal resistance. The nearly square shape of the I–V curve further confirms the efficient operation of the device and the favorable electrical properties introduced by the C-60 material.

Overall, the results demonstrate that C-60 plays a significant role in improving the electrical performance of the solar cells by enhancing electron transport, reducing recombination losses, and increasing the output power. The third sample exhibited the best photovoltaic performance, achieving the highest values of $\mathbf{V_{OC}}$, $\mathbf{J_{SC}}$, and efficiency, which confirms the effectiveness of C-60 in enhancing solar cell operation.

Table (2) shows the relationship between current and voltage for the second sample

Voltage (V)	Current (mA)
0	54
0.08333	54
0.13332	54
0.16666	54
0.29998	54
0.38497	44.1
0.39997	0

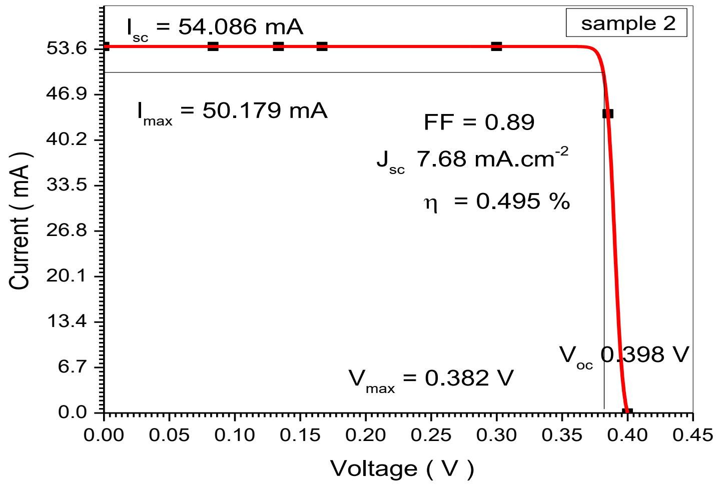

Figure (2) the relationship between current and voltage for the second sample.

The I–V curve of **Sample 2** demonstrates a noticeable improvement compared to Sample 1. The current remains nearly constant over a wider voltage range before dropping sharply near the open-circuit voltage (**V_{OC}**). This behavior is characteristic of a well-performing solar cell and indicates efficient generation, collection, and transport of photogenerated charge carriers.
The nearly rectangular shape of the curve suggests reduced losses due to internal resistance and charge-carrier recombination, resulting in enhanced photovoltaic performance. Furthermore, the sharp decrease in current near the **V_{OC}** region reflects good rectifying characteristics of the active junction within the solar cell.
The improved performance of Sample 2 can be attributed to the positive role of **C-60 (Fullerene)** in enhancing electron transport and reducing charge recombination. C-60 molecules act as efficient electron acceptors, facilitating charge separation and promoting the transport of photogenerated electrons toward the electrodes with higher efficiency.
These observations are consistent with the results presented in the table, where the conversion efficiency increased from **0.182%** in Sample 1 to **0.49%** in Sample 2, while the open-circuit voltage increased from **0.119 V** to **0.3927 V**. This improvement indicates better device quality and a higher ability to convert incident solar energy into electrical energy.
Overall, the results of Sample 2 confirm that the incorporation or optimization of **C-60** contributed significantly to improving the electrical properties of the solar cell, leading to higher output voltage and enhanced conversion efficiency compared with Sample 1, while bringing the device performance closer to the ideal photovoltaic behavior.

Table (3) shows the relationship between current and voltage for the third sample

Voltage (V)	Current (mA)
0	55.01887
0.10555	55.01887
0.16888	55.01887
0.2111	55.01887
0.37998	55.01887
0.48765	44.92663
0.50665	0

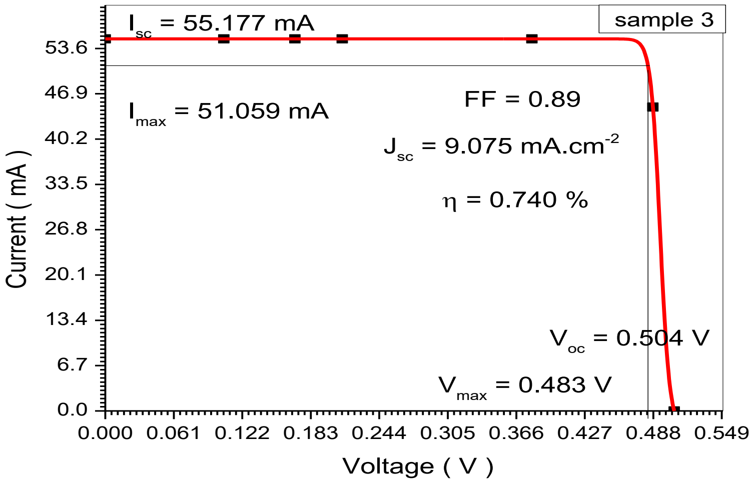

Figure (3) illustrates the relationship between current and voltage for the third sample.

The curve represents the current-voltage (I-V) characteristics of a solar cell modified using Carbon 60 (C-60), where the experimental results demonstrated an overall power conversion efficiency of 0.740% and an open-circuit voltage of 0.504 V. This specific sample (Sample 3) is distinguished by recording an exceptional and remarkably high fill factor of 0.89, which serves as a direct physical indicator of a significant reduction in internal series resistance alongside an improvement in the cell's shunt resistance. This near-ideal, box-like behavior and the sharp stability of the current until the voltage approaches its maximum value are attributed to the unique properties of the fullerene nanostructure, which grants it a superior electron-accepting ability and prevents charge accumulation at the interfaces. Furthermore, the excellent orbital overlapping of Carbon 60 contributes to facilitating charge transport and remarkably minimizing recombination losses during operation. Despite this clear structural excellence in the electron transport mechanism, the overall efficiency of the cell remains limited and below one percent due to the low values of the short-circuit current density, which registered 9.075mA.cm^{-2}. These results demonstrate that incorporating Carbon 60 guarantees high quality in charge separation and collection, yet future approaches to enhance performance require improving the spectral absorption quality of the donor material. Therefore, it is recommended for upcoming research to focus on engineering the interfacial energy levels (HOMO-LUMO) to increase the open-circuit voltage and to optimize the active layer thickness to boost the overall efficiency.

9. Recommendations

1-Investigate the effect of different concentrations of C-60 on solar-cell performance.
2-Optimize the thickness of the active layer to maximize light absorption.
3-Improve energy-level alignment between the different layers of the solar cell.
4-Employ advanced deposition techniques to achieve more uniform thin films.
5-Explore the combination of C-60 with other nanomaterials to further enhance solar-cell efficiency.

10. Conclusion

The study demonstrated that incorporating Carbon-60 (C-60) significantly improved the photovoltaic properties of solar cells by increasing the open-circuit voltage, short-circuit current density, and power conversion efficiency. Furthermore, C-60 enhanced electron transport and reduced charge recombination losses, leading to improved overall device performance. The third sample exhibited the best photovoltaic performance, achieving a conversion efficiency of 0.504%, confirming the effectiveness of C-60 as a promising material for the development of high-performance solar cells.

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