CONVERSION EFFICIENCY AND STABILITY OF ORGANIC SOLAR CELLS INCORPORATING TITANIUM DIOXIDE WITH FULLERENE-BASED ACCEPTOR

NASER KHAMIS AL SHEKAILI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Science
Universiti Teknologi Malaysia

MARCH 2022

DEDICATION

In the name of Allah, the most Gracious, the most Merciful. May Allah's benedictions and salutations be upon to His beloved messenger Muhammad, members of His household and His companions.

This work is dedicated to my parents, brothers, sisters, wife and kids for their love, prayers and support.

ACKNOWLEDGEMENT

First and foremost, I would like to thank God, the almighty Allah, for blessing me with sufficient time and health to achieve my goals. I would like to express my profound gratitude and appreciation to my supervisor, Prof. Dr. Suhairul Bin Hashim. My sincerest thanks are due to him, not only for supervising and overseeing the progress of this work but also for his input, immense knowledge, patience and time. In addition, I would like to express my sincere thanks to my co-supervisor, Assoc. Prof. Dr. Fahmi Fariq Muhammadsharif, for his continuous support and encouragement. I want to say I am grateful for all your advice, assistance, attention, and guidance. Your generosity with time and prompt response to my numerous questions and demands have made this academic journey a fruitful one.

I also deeply appreciate my co-supervisor, Assoc. Prof. Dr. Mohammed Zaher Al-Abri, for providing the suitable and friendly atmosphere of the Nanotechnology laboratory along with modern equipment which allowed me to accomplish such advanced study. I would equally want to extend my thankfulness to Assoc. Prof. Dr. Khaulah Sulaiman from the University of Malaya, who gave me the opportunity to be an internship student in the Low Dimensional Materials Research Centre (LDMRC) for six months. In this research centre, most of the essential results of my Ph.D research were obtained. More thanks go to Hanan Alzahrani, my colleague at the Low Dimensional Material Research Center (LDMRC), Department of Physics, University of Malaya, for her fruitful and kind help. I would like to thank my parents, wife, and kids for their patient, all the love and support they have given me throughout my life. Last but not least, I would like to thank my friends and everyone who is not mentioned here for their contribution, direct or indirect, during the completion of my research work.

ABSTRACT

It is necessary for organic solar cells (OSCs) to have a high and stable power conversion efficiency (PCE) in ambient temperature and at different environmental conditions before they are commercially available on the market. However, the efficiency and stability of OSCs are limited by the type, structure, and architectural design of their active layers. Therefore, the main focus of the current research is to find an appropriate method to improve the efficiency and stability of OSCs. In this study, five different approaches were used with the aim of improving the efficiency and stability of OSCs based on PTB7:$PC_{71}BM$ blend. The first one is assigned to optimize the PTB7:$PC_{71}BM$ active layer thickness of the OSC devices. The second method explores the impact of TiO_2 nanostructures on the physical properties and electrical performance of OSCs based on PTB7:$PC_{71}BM$ bulk heterojunctions. The third approach is devoted to studying the rate of improvement in the overall performance of PTB7:$PC_{71}BM$-based OSCs by using TiO_2 as an electron transport layer (ETL). The fourth method investigates the effect of thermal annealing treatment on stability, reproducibility, and photovoltaic performance. The fifth approach presents the hot substrate coating method as a novel strategy to improve the PTB7:$PC_{71}BM$-based OSC in terms of stability and photovoltaic performance. For the active layer thickness optimization, results revealed that the OSC based on PTB7:$PC_{71}BM$ with a 70 nm thickness showed the best PCE of 5.63%. After incorporating 10% TiO_2 into the PTB7:$PC_{71}BM$ blend and annealing at 100 °C, an unexpectedly low efficiency of 0.08% was obtained. Alternatively, the performance improvement of the PTB7:$PC_{71}BM$-based OSCs was achieved by using a very thin layer of titanium oxide (TiO) as ETL. Results showed that with the use of 5 nm TiO (ETL), the PCE was improved from 5.6% to 9.63%. Moreover, results demonstrated an improvement in the OSCs efficiency when they were annealed at 50 °C, with a reported PCE of 9.75%, which is considered to be the highest efficiency reported for the single junction OSC based on PTB7:$PC_{71}BM$. The device annealed at 50 °C exhibited higher stability and better reproducibility than the un-annealed device. The last strategy performed in this research is called hot substrate-coating method. In this method, two different batches of OSCs were fabricated on hot substrate and room temperature (RT) substrate under similar environmental conditions. Results showed that OSCs fabricated via hot substrate-coating presented a PCE of 7.94% compared to 5.6% for the RT-coated device. The hot substrate-coated device retained 83% of its initial PCE after 20 days of operation, considered to be the highest stability achieved for the single junction OSC based on PTB7:$PC_{71}BM$. The proposed hot substrate-coating approach could be utilized to improve both the efficiency and stability of OSCs.

ABSTRAK

Sel suria organik (OSC) perlu mempunyai kecekapan penukaran kuasa (PCE) yang tinggi dan stabil di suhu ambien dan pada keadaan persekitaran yang berbeza sebelum tersedia secara dagangan di pasaran. Walau bagaimanapun, kecekapan dan kestabilan OSC dibatasi oleh jenis, struktur, dan reka bentuk seni bina lapisan aktifnya. Oleh itu, fokus utama penyelidikan semasa adalah mencari kaedah yang sesuai untuk meningkatkan kecekapan dan kestabilan OSC. Dalam kajian ini, lima pendekatan berbeza telah digunakan dengan tujuan untuk meningkatkan kecekapan dan kestabilan OSC berdasarkan adunan PTB7:$PC_{71}BM$. Pendekatan pertama adalah untuk mengoptimumkan ketebalan lapisan aktif PTB7:$PC_{71}BM$ pada peranti OSC. Kaedah kedua meneroka kesan nanostruktur TiO_2 ke atas sifat fizikal dan prestasi elektrik OSC berasaskan PTB7:$PC_{71}BM$ hetero-simpang pukal. Pendekatan ketiga ditumpukan untuk mengkaji kadar peningkatan prestasi keseluruhan OSC berasaskan PTB7:$PC_{71}BM$ dengan menggunakan TiO_2 sebagai lapisan pengangkutan elektron (ETL). Kaedah keempat, menyiasat kesan rawatan penyepuhlindapan terma terhadap kestabilan, kebolehulangan semula, dan prestasi fotovolta. Pendekatan kelima mengemukakan kaedah penyalutan substrat panas sebagai strategi baru untuk meningkatkan OSC berasaskan PTB7:$PC_{71}BM$ dari segi kestabilan dan prestasi fotovolta. Untuk pengoptimuman ketebalan lapisan aktif, dapatan menunjukkan bahawa OSC berasaskan PTB7:$PC_{71}BM$ dengan ketebalan 70 nm menunjukkan PCE terbaik pada 5.63%. Setelah memasukkan 10% TiO_2 ke dalam adunan PTB7:$PC_{71}BM$ dan penyepuhlindapan pada suhu 100 °C, kecekapan rendah yang tidak dijangka sebanyak 0.08% diperoleh. Sebagai alternatif, peningkatan prestasi OSC berasaskan PTB7:$PC_{71}BM$ dicapai dengan menggunakan lapisan titanium oksida (TiO) yang sangat tipis sebagai ETL. Dapatan kajian menunjukkan bahawa dengan penggunaan TiO 5 nm (ETL), PCE telah meningkat daripada 5.6% kepada 9.63%. Selain itu, dapatan menunjukkan pembaikan dalam kecekapan OSC apabila disepuhlindap pada 50 °C, dengan PCE yang dilaporkan sebanyak 9.75%, yang dianggap sebagai kecekapan tertinggi yang dilaporkan untuk OSC simpang tunggal berdasarkan PTB7:$PC_{71}BM$. Peranti yang disepuhlindap pada suhu 50 °C menunjukkan kestabilan yang lebih tinggi dan kebolehulangan semula yang lebih baik daripada peranti tanpa disepuhlindap. Strategi terakhir yang dilakukan dalam penyelidikan ini dipanggil kaedah salutan substrat panas. Dalam kaedah ini, dua kelompok OSC yang berbeza telah difabrikat pada substrat panas dan substrat suhu bilik (RT) di bawah keadaan persekitaran yang sama. Dapatan menunjukkan bahawa OSC yang difabrikat melalui salutan substrat panas memberikan PCE sebanyak 7.94% berbanding 5.6% untuk peranti bersalut RT. Peranti bersalut substrat panas mengekalkan 83% daripada PCE awalnya selepas 20 hari beroperasi, dianggap mencapai kestabilan tertinggi yang dicapai untuk OSC simpang tunggal berdasarkan PTB7:$PC_{71}BM$. Pendekatan salutan substrat panas yang dicadangkan boleh digunakan untuk memperbaiki kecekapan dan kestabilan OSC.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Al	-	Aluminium
TiO_2	-	Titanium dioxide
OSCs	-	Organic solar cells
IPCE	-	Incident Photon-to-Current Conversion Efficiency
D-A	-	Donor-Acceptor
AM	-	Air mass
BHJ	-	Bulk heterojunction
ITO	-	Indium-tin-oxide
PCE	-	Power Conversion Efficiency
ETL	-	Electron transporting layer
EBL	-	Exciton blocking layer
PEDOT:PSS	-	poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)
$PC_{71}BM$	-	(6,6)-phenyl C71 butyric acid methyl ester
UV-Vis-	-	
NIR		Ultraviolet-Visible-Near Infrared
VB	-	Valence band
CB	-	Conduction band
IP	-	Ionization potential
EA	-	Electron affinity
c-Si	-	crystalline silicon
HTL	-	Hole transporting layer
RMSE	-	Root mean square error
NP	-	Nanoparticle
DCB	-	Dichlorobenzene
CLB	-	Chlorobenzene
SEM	-	Scanning Electron Microscope
EQE	-	External Quantum Efficiency
FTIR	-	Fourier Transform Infrared
HOMO	-	Higher Occupied Molecular Orbital
AFM	-	Atomic Force Microscopy

D	-	Donor
LUMO	-	Lower Unoccupied Molecular Orbital
A	-	Acceptor
PL	-	Photoluminescence
PV	-	Photovoltaic
TBHJ	-	Ternary Bulk Heterojunction
HSCs	-	Hybrid Solar Cells
XRD	-	X-ray Diffraction

LIST OF SYMBOLS

I_{sc}	-	Short circuit current
λ	-	Wavelength
n	-	Ideality factor
θ	-	Angle of diffraction
P_{max}	-	Maximum output power
V_{max}	-	Maximum output voltage
J_{max}	-	Maximum output current density
I_{max}	-	Current at maximum power
P_{in}	-	Input power
R_s	-	Series resistance
R_{sh}	-	Shunt resistance
η	-	Power conversion efficiency
E_g	-	Energy band gap
FF	-	Fill Factor
V_{oc}	-	Open-circuit voltage
J_{sc}	-	Short circuit current density
N_e		Number of electrons measured as photocurrent in the external circuit
N_p	-	Number of photons striking the solar cell in unit time

CHAPTER 1

INTRODUCTION

1.1 Overview

Energy is considered an essential contributor to the economic, technological, and social development of every country. World energy consumption is continuously increasing, and the developed countries comprise a major share of this consumption (L.-q. Liu et al., 2010). This in turn leads to a scarcity in the main sources of energy such as petroleum, natural gas, and coal. However, the widespread use of fossil fuels in satisfying the daily human need for energy is expected to negatively impact the foreseeable future. This motivates the utilization of renewable energy sources such as solar energy to produce clean and environmentally friendly electricity by means of solar cells through photovoltaic (PV) technology (Hegedus & Luque, 2011). The vast majority of solar cells available on the market are based on inorganic semiconductors that are recognised as being high-cost devices due to the high energy requirement for purifying the materials and complex instrumentation used for fabricating the devices (Brabec, 2004).

The alternative candidate to inorganic solar cell for photovoltaic applications is its organic counterpart, which has the benefit of high productivity and solution phase processing, and therefore resulting in low-cost electricity production. Several important features offered by OSCs include solution processability, flexibility, light weight and low cost of cell fabrication (Abdel-Fattah et al., 2015; Lu et al., 2014; Sharenko et al., 2014; Vijay & Sumaria, 2014). Moreover, it can be manufactured in an environmentally friendly and economical process with high mechanical flexibility (Supasai et al., 2017). Organic semiconductors are well known for their unique properties, which allow them to be deployed in various electronic devices such as solar cells, laser diodes, light-emitting diodes and thin-film transistors (Moiz et al., 2016; Wu et al., 2014). In addition, there are yet room for OSCs to achieve higher efficiency

(Holliday et al., 2016; Wan et al., 2016), stability (Abdullah et al., 2015; Omrane et al., 2011), and lifetime (Espinosa et al., 2011; Wang et al., 2011), compared to inorganic solar cells.

Organic solar cells (OSC) contain conjugated polymers and small molecular materials that are widely used as a bulk heterojunction (BHJ) structure. Conjugated polymers have the advantage of being soluble in common organic solvents, allowing them to be deposited using simple solution processing and printing techniques. As a result, they can be easily fabricated at a lower cost compared to the inorganic semiconductor devices.

While conjugated polymers or small molecules are the most commonly employed donors, Perylene diimide and fullerene derivatives are the most commonly utilized acceptor materials. Because pristine C_{60} has a low solubility, it is necessary to find a soluble fullerene derivative for efficient OSCs. Therefore, the new synthesized fullerene derivatives, such as $PC_{61}BM$ and $PC_{71}BM$, which are highly soluble in aromatic solvents and have a higher electron acceptor efficiency than pristine C_{60}, pave the path for improved OSC performance. Due to their broad and high UV–vis absorption, adequate energy levels, material miscibility, and better charge transporting characteristics, various functionalized fullerene derivatives have been reported with improved efficiency (Ganesamoorthy et al., 2017).

Bulk heterojunction structure has been extensively used as a photoactive layer system for OSC devices. This is because BHJs increase the interfaces between the donor and the acceptor materials, thereby facilitating large exciton dissociation (Muhammad et al., 2018). This structure is built up with two different types of organic semiconducting materials, an electron donor (polymer) and an electron acceptor (fullerene). These two materials are mixed together at nanoscale and provide a bi-continuous interpenetrating network which in turn facilitates exciton dissociation and charge transport. Moreover, this structure helps in transporting the holes and electrons along the active layer regions and facilitating their collection at their respective electrodes (Supasai et al., 2017). Overall, it has been noticed in the last few years that using the BHJ structure showed the most significant improvements (Li et al., 2017; Zhang et al., 2019).

A bulk heterojunction blend of P3HT and $PC_{61}BM$ that form the interconnection of donor/acceptor components has been widely used for OSCs fabrication (Ameri et al., 2012; Wu et al., 2014). OSCs based on fluorinated thieno [3,4-b] thiophene family, the poly[(4,8-bis -(2-ethylhexyloxy)-benzo(1,2-b:4,5-b0) dithiophene)-2,6-diyl-alt-(4-(2ethylhexyl)-3fluorothieno [3,4-b]thiophene-)-2-carboxylate-2-6-diyl)] (PTB7) as the electron donor combined with [6,6]-phenyl C_{71} butyric acid methyl ester ($PC_{71}BM$) as the electron acceptor have diverted attention away from P3HT:PCBM system due to their high performance as BHJ solar cells (Barreiro-Argüelles et al., 2018; Ciammaruchi et al., 2016; Sánchez et al., 2017; Sharma et al., 2019; Zhang et al., 2019).

1.2 Problem Statement

In OSCs, it is known that there is a limit on the selection of active layer thickness for optimum performance. It was revealed that a thin-film active layer has a limitation on the absorption of sunlight photons, while a thicker film that absorbs more photons could cause large bulk resistance and weaken carrier transport (Chen et al., 2013). Moreover, a thicker active layer has a high potential for electron-hole recombination, while the very thin active layer exhibits fewer traps and improves charge-transfer properties (Zhang et al., 2019). Therefore, finding the optimum active layer thickness, which combines strong absorption with efficient charge carrier collection, is considered a challenge for thin film solar cells. Thus, before the solar cell devices are fabricated, the thickness of the active layer must be optimized.

Common organic semiconductors possess a relatively wide energy gap (Eg) of more than 2 eV, which is not practically useful for achieving a broad band of light absorption or collecting a large portion of the solar spectrum. Solar cells incorporated with metal or metal oxide nanoparticles can be an efficient solution to the absorption problem in OSCs due to the high absorption coefficient and higher photoconductivity of metal/metal oxides compared to those of organic semiconductors. This hybrid approach leads to improve photon harvesting in the OBHJ (Çaldıran et al., 2017). The strategy behind dispersing inorganic nanoparticles (NPs) throughout organic active layers is therefore raised from the concept of combining the important properties of these two materials in one hybrid active layer, such as improved absorption and boosted photo-generation of charge carriers (Günes et al., 2007). Considerable attention has been paid to the development of hybrid solar cells (HSCs), focusing on the benefits of the unique properties of organic materials including low cost, flexibility, and light weight, in addition to high conductivity and good thermal stability of inorganic nanoparticles (Wright & Uddin, 2012). The utilization of ternary active layers in organic solar cells is one of the attractive approaches that is usually used to broaden their absorption of the solar spectrum.

The third component of the ternary active layer is usually a donor material, which stimulates photoelectric activity, thereby enhancing the light absorption devices (A. Kumar et al., 2016). The inorganic nanostructures are known to have unique electrical and thermal properties in terms of charge transportation and stability (Chen et al., 2017), which can be alternatively utilized as a third component of ternary bulk heterojunction. For this reason, the appropriate metal oxide nanoparticles to be incorporated in the OSC active layer must be found, with the aim of enhancing light harvesting and improving OSC efficiency through the application of bulk heterojunctions (BHJ) concept.

Moreover, charge transport response, chemical degradation of active layer, oxidation of metal electrodes caused by moisture, oxygen and/or light and the phase separation of organic blends are considered as the most common factors that lead to degradation of OSCs (Foe et al., 2014). An efficient strategy used to overcome these obstacles and improve OSC performance is to insert an interfacial layer between the active layer and metal top electrode in both conventional OSCs and inverted ones (Abdel-Fattah et al., 2015). This strategy also acts upon improving junction conductivity, thereby increasing charge transportation. Consequently, there would be a good chance of decreasing the charge recombination rate and improving light absorption, which in turn increases the photocurrent of the solar cells (Gilot et al., 2007). Furthermore, the charge transport layer acts as an insulator between the active layer and the metal electrode, which has the benefit of minimizing charge leakage and charge recombination.

Different materials like metal oxides, conjugated polyelectrolytes (CPEs), and self-assembled monolayers (SAMs) can support electron transportation between the active layer and the cathode, consequently enhancing the photovoltaic device's performance when they are utilised as interfacial materials (Zhou et al., 2013). Therefore, finding a proper material that can be used as an ETL and optimizing its thickness is important for the improvement in the performance of organic solar cells. Therefore, after selecting the ETL material, the thickness of the ETL needs to be optimized.

OSCs devices that are intended for commercial use are highly recommended to have high and stable PCEs under ambient conditions. To improve the efficiency and the stability of OSCs, various methods have been used such as rearranging the stacked layers, choosing highly efficient donor and acceptor materials, using different electrodes for charge carrier collection, and applying precise encapsulations to minimise the degradation of metal electrodes and organic materials (Cai et al., 2010; Jørgensen et al., 2012; Sánchez et al., 2017). On the other hand, several strategies have been used in the fabrication process to boost the performance of OSCs such as thermal annealing (Savikhin et al., 2018; Supasai et al., 2017; Zhong et al., 2016), solvent vapour annealing (Yu et al., 2017; Zheng et al., 2014), mixed solvent (Chen et al., 2013; L. Wang et al., 2016), interface modification (Borse et al., 2017; Lu et al., 2014; G. Wang et al., 2014), and so on. Therefore, thermal annealing is applied on the OSC devices based on PTB7:$PC_{71}BM$ blend aiming at improving the device efficiency, stability and reproducibility.

One of the reasons for low efficiency and degradation of OSC active layer film coated on RT substrate is the relatively high gaps between donor and acceptor moieties as well as higher surface roughness and poor adhesion between the active layer film and the HTL surface, which negative impact the OSC performance (Yu et al., 2018). These obstacles could be avoided by using a method called hot substrate-coating. This method could provide a fast solvent evaporation and rapid nucleation, which in turn stimulates the active layer to be improved by forming a better surface coverage and remarkably improved morphology with smaller voids. Consequently, the quality of the deposited films and the device performance in terms of stability and reproducibility can be improved.

1.3 Objectives of Study

The aims of this study are summarized as follows:

i. To investigate the effect of thickness in both organic solar cell (OSC) active layer and electron transport layer (ETL) in terms of photovoltaic performance.
ii. To evaluate the impact of titanium dioxide (TiO_2) nanostructures on the physical properties and performance of organic solar cells based on PTB7:$PC_{71}BM$ bulk heterojunctions under different device architectures of TiO_2 inclusion.
iii. To determine the influence of temperature, through active layers annealing and hot-substrate method, on the performance, stability, and reproducibility of OSCs based on PTB7:$PC_{71}BM$ blends.

1.4 Scope of the Study

This particular project focuses on the improvement of the organic solar cells in terms of efficiency, stability and reproducibility. Key factors as following scopes will be discussed.

i. The current study focuses on the growth and broad characterization of a ternary active layer incorporating inorganic nanostructures of TiO_2 which can be alternatively utilized as a third component of ternary bulk heterojunction for the application of solution-processed hybrid solar cells. The donor and acceptor components are PTB7 and $PC_{71}BM$, respectively. The nanostructures of TiO_2 is incorporated to produce a solution-processable ternary active layer based on PTB7:$PC_{71}BM$:TiO_2. The weight ratio of PTB7:$PC_{71}BM$ will be kept constant (1:1.5), while the weight ratio of the dopant material of TiO_2 nanostructures is varied to achieve different concentrations of 10%, 20% and 30%. Therefore, the current work is devoted to studying the impact of incorporating TiO_2 nanostructures on the photovoltaic performance and the optoelectronic properties of organic solar cells based on PTB7:$PC_{71}BM$ bulk heterojunctions. In addition, the effects of thermal annealing under vacuum condition on the optical and structural behaviours of the PTB7:$PC_{71}BM$:TiO_2 ternary BHJ blend are investigated.

ii. In the current study, (3,4-ethylenedioxythiophene): poly (4-styrenesulfonate) (PEDOT:PSS) is used as a hole transporting layer (HTL) deposited between the ITO electrode and the active layer under room temperature and ambient conditions.

iii. This work is devoted to further studying the rate of improvement in the overall performance of PTB7:$PC_{71}BM$ based OSCs by using TiO_2 as the ETL. In this way, active layer and ETL thicknesses are first optimized by fabricating several devices with different active layer thicknesses without the inclusion of TiO_2 ETL. Then, the one with the best efficiency is chosen to be improved through the addition of TiO_2 based ETL with different thicknesses. The deposition of TiO_2 was performed via thermal evaporation inside a vacuum chamber through a shadow mask at a pressure of 10^{-4} Pa. TiO_2 layer thickness was carefully controlled by using a high vacuum thermal deposition system (PVD) in order to obtain thicknesses of 1 nm, 5 nm and 10 nm. In this work, thermal evaporation is also applied to produce the top aluminium electrode of the solar cells.

iv. The current study was carried out to investigate the impact of thermal annealing on the OSC devices based on PTB7:$PC_{71}BM$ blend, with the inclusion of TiO_2

as a buffer layer between the active layer and the Al electrode. Different annealing temperatures were applied on the OSC devices with architecture ITO/PEDOT:PSS/PTB7:$PC_{71}BM$/TiO_2/Al, and electrically characterized to determine which annealing temperature yields the highest device efficiency, stability, and reproducibility. All the fabricated devices were exposed to different heat treatment, with temperatures ranging from 50 °C to 150 °C with steps of 50 °C for 20 min inside the glove box under a nitrogen atmosphere.

v. The hot substrate coating method was carried out in this study as a novel strategy aiming to improve the efficiency, stability and reproducibility of organic solar cells based on PTB7:$PC_{71}BM$ blend. In this method, the ITO substrates temperature were kept at 150 °C during the deposition of the active layer by using spin coater.

vi. The deposition of all active layers is made from solution using a spin coater at room temperature inside a glove box. The nanostructures obtained will be characterized by various techniques, such as UV-Vis spectroscopy, PL spectroscopy, X-ray diffraction (XRD) technique, Atomic Force Microscopy (AFM), and surface profilometer, to reveal their optical, structural and morphological properties. The main parameters that are used to characterize the performance of the solar cell include the open-circuit voltage (V_{oc}), the short-circuit current density (J_{sc}), the fill factor (FF) and the power conversion efficiency (η).

1.5 Significance of Study

The active layer is considered as the major efficient layer in OSCs, as it absorbs the light photons and produces excitons, so its thickness significantly dictates the cell's performance. Therefore, this study presents the importance of selecting the optimum active layer thickness for obtaining higher photovoltaic performance from the PTB7:$PC_{71}BM$ blend. Moreover, light harvesting in the organic active layer could be enhanced by incorporating metal oxide nanoparticles into the active layer blend, forming a bulk heterojunction structure. This improvement in photon absorption is due to the high absorption coefficients and higher photoconductivity of metal/metal oxides compared to those of organic semiconductors. The inorganic nanostructures are known to have unique electrical and thermal properties in terms of charge transportation and stability (Chen et al., 2017), which can be alternatively utilized as the third component of a ternary bulk heterojunction. Special attention has been paid to titanium dioxide (TiO_2) due to its attractive photocatalytic properties and excellent chemical, optical and electrical properties (Bedikyan et al., 2013). Therefore, this study presents knowledge on the effect of the incorporation of TiO_2 into the organic active layer forming hybrid structures based on PTB7:$PC_{71}BM$:TiO_2 for enhancing and broadening the light absorption in OSCs.

Thermal annealing can show great potential in enhancing the optoelectronic properties of the polymer blend (Vijay & Sumaria, 2014). This enhancement occurs due to better nanoscale morphology and crystallization of the polymers, which in turn can increase charge carrier mobility and reduce recombination (Mola et al., 2016). Thus, the current study presents an investigation on the impact of thermal annealing on OSC devices with the architecture ITO/PEDOT:PSS/PTB7:$PC_{71}BM$/TiO_2/Al, to determine which annealing temperature would yield the highest device efficiency, stability and reproducibility.

Several materials like metal oxides, CPEs, and SAMs can facilitate electron transfer between the active layer and the cathode, thereby increasing the performance of photovoltaic devices when used as interface materials (Zhou et al., 2013). TiO_2 was successfully used as ETL due to its high absorption coefficient (Yun & Sulaiman, 2011), high electron mobility, environmentally friendliness with a comparatively low price and excellent chemical and physical stability (Huang et al., 2011). Hence, one of the importance of the current study is contributing to the enhancement of OSCs in terms of photovoltaic performance, stability and reproducibility.

1.6 Thesis Outline

The current thesis consists of 5 main chapters organized as follows. Chapter 1 describes the research outline, which includes a brief introduction revealing the need for an alternative candidate to inorganic solar cell for photovoltaic applications followed by the problem statement and objectives of the current work. Later on, the scope and the significance of the research is given. Chapter 2 includes an introduction that presents the reasons behind utilizing organic solar cells in brief, then moves to a brief history of solar cell types with the highest reported power conversion efficiencies (PCE). Moreover, it discusses the most important parameters which define the performance of the solar cells. Finally, it reviews the organic and inorganic materials used in this study. Chapter 3 describes experimental setup and procedures, including substrate preparation, solutions preparation, thin-film coating, thin-film characterization, device fabrication, and device characterization. Chapter 4 describes the most important results that were obtained from the experimental works. Finally, chapter 5 reports the main conclusions that were drawn from the results and recommendations for future research.

REFERENCES

Abdel-Fattah, T. M., Younes, E. M., Namkoong, G., El-Maghraby, E., Elsayed, A. H., & Elazm, A. A. (2015). Stability study of low and high band gap polymer and air stability of PTB7: PC71BM bulk heterojunction organic photovoltaic cells with encapsulation technique. *Synthetic Metals, 209*, 348-354.

Abdullah, S. M., Ahmad, Z., & Sulaiman, K. (2015). The impact of thermal annealing to the efficiency and stability of organic solar cells based on PCDTBT: PC71BM. *Procedia-Social and Behavioral Sciences, 195*, 2135-2142.

Ahlswede, E., Mühleisen, W., bin Moh Wahi, M. W., Hanisch, J., & Powalla, M. (2008). Highly efficient organic solar cells with printable low-cost transparent contacts. *Applied Physics Letters, 92*(14), 127.

Al-Shekaili, N., Hashim, S., Muhammadsharif, F. F., MZ, A.-A., Sulaiman, K., Yahya, M. Y., & Ahmad, M. R. (2020). Enhanced Performance of PTB7: PC71BM Based Organic Solar Cells by Incorporating a Nano-Layered Electron Transport of Titanium Oxide. *ECS Journal of Solid State Science and Technology, 9*(10), 105003.

Alem, S., Chu, T.-Y., Shing, C. T., Wakim, S., Lu, J., Movileanu, R., Tao, Y., Bélanger, F., Désilets, D., & Beaupré, S. (2011). Effect of mixed solvents on PCDTBT: PC70BM based solar cells. *Organic Electronics, 12*(11), 1788-1793.

Ameri, T., Min, J., Li, N., Machui, F., Baran, D., Forster, M., Schottler, K. J., Dolfen, D., Scherf, U., & Brabec, C. J. (2012). Performance enhancement of the P3HT/PCBM solar cells through NIR sensitization using a small-bandgap polymer. *Advanced Energy Materials, 2*(10), 1198-1202.

Arbab, E. A., Taleatu, B. A., & Mola, G. T. (2015). Ternary molecules blend organic bulk heterojunction solar cell. *Materials science in semiconductor processing, 40*, 158-161.

Armstrong, N. R., Veneman, P. A., Ratcliff, E., Placencia, D., & Brumbach, M. (2009). Oxide contacts in organic photovoltaics: Characterization and control of near-surface composition in indium− tin oxide (ITO) electrodes. *Accounts of chemical research, 42*(11), 1748-1757.

Baek, W.-H., Yang, H., Yoon, T.-S., Kang, C., Lee, H. H., & Kim, Y.-S. (2009). Effect of P3HT: PCBM concentration in solvent on performances of organic solar cells. *Solar Energy Materials and solar cells, 93*(8), 1263-1267.

Barreiro-Argüelles, D., Ramos-Ortiz, G., Maldonado, J.-L., Pérez-Gutiérrez, E., Romero-Borja, D., Meneses-Nava, M.-A., & Nolasco, J. C. (2018). Stability study in organic solar cells based on PTB7: PC71BM and the scaling effect of the active layer. *Solar Energy, 163*, 510-518.

Bedikyan, L., Zakhariev, S., & Zakharieva, M. (2013). Titanium dioxide thin films: preparation and optical properties. *Journal of Chemical Technology and Metallurgy, 48*(6), 555-558.

Bhushan, B. (2010). *Scanning probe microscopy in nanoscience and nanotechnology 2*. Springer Science & Business Media.

Blom, P. W., Mihailetchi, V. D., Koster, L. J. A., & Markov, D. E. (2007). Device physics of polymer: fullerene bulk heterojunction solar cells. *Advanced materials, 19*(12), 1551-1566.

Bogner, A., Jouneau, P.-H., Thollet, G., Basset, D., & Gauthier, C. (2007). A history of scanning electron microscopy developments: Towards “wet-STEM” imaging. *Micron, 38*(4), 390-401.

Borse, K., Sharma, R., Sagar, H., Reddy, P. A., Gupta, D., & Yella, A. (2017). Efficient light trapping and interface engineering for performance enhancement in PTB7-Th: PC70BM organic solar cells. *Organic Electronics, 41*, 280-286.

Brabec, C. J. (2004). Organic photovoltaics: technology and market. *Solar Energy Materials and solar cells, 83*(2-3), 273-292.

Brabec, C. J., & Durrant, J. R. (2008). Solution-processed organic solar cells. *MRS bulletin, 33*(7), 670-675.

Brumbach, M., Veneman, P. A., Marrikar, F. S., Schulmeyer, T., Simmonds, A., Xia, W., Lee, P., & Armstrong, N. R. (2007). Surface composition and electrical and electrochemical properties of freshly deposited and acid-etched indium tin oxide electrodes. *Langmuir, 23*(22), 11089-11099.

Bull, T. A., Pingree, L. S., Jenekhe, S. A., Ginger, D. S., & Luscombe, C. K. (2009). The role of mesoscopic PCBM crystallites in solvent vapor annealed copolymer solar cells. *ACS nano, 3*(3), 627-636.

Cai, W., Gong, X., & Cao, Y. (2010). Polymer solar cells: recent development and possible routes for improvement in the performance. *Solar Energy Materials and solar cells, 94*(2), 114-127.

Çaldıran, Z., Biber, M., Metin, Ö., & Aydoğan, Ş. (2017). Improving the performance of the organic solar cell and the inorganic heterojunction devices using monodisperse Fe3O4 nanoparticles. *Optik, 142*, 134-143.

Cao, H., He, W., Mao, Y., Lin, X., Ishikawa, K., Dickerson, J. H., & Hess, W. P. (2014). Recent progress in degradation and stabilization of organic solar cells. *Journal of Power Sources, 264*, 168-183.

Cao, W., Li, J., Chen, H., & Xue, J. (2014). Transparent electrodes for organic optoelectronic devices: a review. *Journal of Photonics for energy, 4*(1), 040990.

Cha, H., Chung, D. S., Bae, S. Y., Lee, M. J., An, T. K., Hwang, J., Kim, K. H., Kim, Y. H., Choi, D. H., & Park, C. E. (2013). Complementary absorbing starshaped small molecules for the preparation of ternary cascade energy structures in organic photovoltaic cells. *Advanced Functional Materials, 23*(12), 1556-1565.

Chen, C. C., Chang, W. H., Yoshimura, K., Ohya, K., You, J., Gao, J., Hong, Z., & Yang, Y. (2014). An efficient triple-junction polymer solar cell having a power conversion efficiency exceeding 11%. *Advanced materials, 26*(32), 5670-5677.

Chen, H.-Y., Lin, S.-H., Sun, J.-Y., Hsu, C.-H., Lan, S., & Lin, C.-F. (2013). Morphologic improvement of the PBDTTT-C and PC71BM blend film with mixed solvent for high-performance inverted polymer solar cells. *Nanotechnology, 24*(48), 484009.

Chen, Z., Du, X., Zeng, Q., & Yang, B. (2017). Recent development and understanding of polymer–nanocrystal hybrid solar cells. *Materials Chemistry Frontiers, 1*(8), 1502-1513.

Ciammaruchi, L., Brunetti, F., & Visoly-Fisher, I. (2016). Solvent effects on the morphology and stability of PTB7: PCBM based solar cells. *Solar Energy, 137*, 490-499.

Clarke, T. M., & Durrant, J. R. (2010). Charge photogeneration in organic solar cells. *Chemical reviews, 110*(11), 6736-6767.

Cui, Y., Yao, H., Zhang, J., Zhang, T., Wang, Y., Hong, L., Xian, K., Xu, B., Zhang, S., & Peng, J. (2019). Over 16% efficiency organic photovoltaic cells enabled by a chlorinated acceptor with increased open-circuit voltages. *Nature communications, 10*(1), 1-8.

Dang, M. T., Hirsch, L., Wantz, G., & Wuest, J. D. (2013). Controlling the morphology and performance of bulk heterojunctions in solar cells. Lessons learned from the benchmark poly (3-hexylthiophene):[6, 6]-phenyl-C61-butyric acid methyl ester system. *Chemical reviews, 113*(5), 3734-3765.

Dang, M. T., Wantz, G., Bejbouji, H., Urien, M., Dautel, O. J., Vignau, L., & Hirsch, L. (2011). Polymeric solar cells based on P3HT: PCBM: Role of the casting solvent. *Solar Energy Materials and solar cells, 95*(12), 3408-3418.

de Arquer, F. P. G., Armin, A., Meredith, P., & Sargent, E. H. (2017). Solution-processed semiconductors for next-generation photodetectors. *Nature Reviews Materials, 2*(3), 1-17.

Dennler, G., & Sariciftci, N. S. (2005). Flexible conjugated polymer-based plastic solar cells: From basics to applications. *Proceedings of the IEEE, 93*(8), 1429-1439.

Dharma, J., Pisal, A., & Shelton, C. (2009). Simple method of measuring the band gap energy value of TiO2 in the powder form using a UV/Vis/NIR spectrometer. *Application Note Shelton, CT: PerkinElmer*.

Ding, Z., Kettle, J., Horie, M., Chang, S.-W., Smith, G. C., Shames, A. I., & Katz, E. A. (2016). Efficient solar cells are more stable: the impact of polymer molecular weight on performance of organic photovoltaics. *Journal of Materials Chemistry A, 4*(19), 7274-7280.

Djurišić, A., Kwong, C., Chui, P., & Chan, W. (2003). Indium–tin–oxide surface treatments: Influence on the performance of CuPc/C 60 solar cells. *Journal of applied physics, 93*(9), 5472-5479.

Dkhil, S. B., Pfannmöller, M., Saba, M. I., Gaceur, M., Heidari, H., Videlot-Ackermann, C., Margeat, O., Guerrero, A., Bisquert, J., & Garcia-Belmonte, G. (2017). Toward high-temperature stability of PTB7-based bulk heterojunction solar cells: impact of fullerene size and solvent additive. *Advanced Energy Materials, 7*(4), 1601486.

Dong, C., Han, X., Zhao, Y., Li, J., Chang, L., & Zhao, W. (2018). A Green Anti-Solvent Process for High Performance Carbon-Based CsPbI2Br All-Inorganic Perovskite Solar Cell. *Solar RRL, 2*(9), 1800139.

Duan, C., Peng, Z., Colberts, F. J., Pang, S., Ye, L., Awartani, O. M., Hendriks, K. H., Ade, H., Wienk, M. M., & Janssen, R. A. (2019). Efficient thick-film polymer solar cells with enhanced fill factors via increased fullerene loading. *ACS applied materials & interfaces, 11*(11), 10794-10800.

Dyakonov, V. (2004). Mechanisms controlling the efficiency of polymer solar cells. *Applied Physics A, 79*(1), 21-25.

El-Shimy, M., & Abdo, T. (2014). Photovoltaic Technologies: History, Advances, and Characterization. *Encycl. Energy Eng. Technol*, 1397-1424.

El Haimeur, A., Makha, M., Bakkali, H., González-Leal, J., Blanco, E., Dominguez, M., & Voitenko, Z. (2020). Enhanced performance of planar perovskite solar cells using dip-coated TiO2 as electron transporting layer. *Solar Energy, 195*, 475-482.

Epp, J. (2016). X-ray diffraction (XRD) techniques for materials characterization. In *Materials characterization using nondestructive evaluation (NDE) methods* (pp. 81-124). Elsevier.

Espinosa, N., Garcia-Valverde, R., Urbina, A., & Krebs, F. C. (2011). A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. *Solar Energy Materials and solar cells, 95*(5), 1293-1302.

Fan, B., Zhang, D., Li, M., Zhong, W., Zeng, Z., Ying, L., Huang, F., & Cao, Y. (2019). Achieving over 16% efficiency for single-junction organic solar cells. *Science China Chemistry, 62*(6), 746-752.

Foe, K., Namkoong, G., Samson, M., Younes, E. M., Nam, I., & Abdel-Fattah, T. M. (2014). Stability of high band gap P3HT: PCBM organic solar cells using TiOx interfacial layer. *International Journal of Photoenergy, 2014*.

Ganesamoorthy, R., Sathiyan, G., & Sakthivel, P. (2017). Fullerene based acceptors for efficient bulk heterojunction organic solar cell applications. *Solar Energy Materials and solar cells, 161*, 102-148.

Ghosh, A. K., & Feng, T. (1978). Merocyanine organic solar cells. *Journal of applied physics, 49*(12), 5982-5989.

Gilot, J., Barbu, I., Wienk, M. M., & Janssen, R. A. (2007). The use of ZnO as optical spacer in polymer solar cells: theoretical and experimental study. *Applied Physics Letters, 91*(11), 113520.

Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Ho-Baillie, A. W. (2020). Solar cell efficiency tables (Version 55). *Progress in Photovoltaics: Research and Applications, 28*(1), 3-15.

Günes, S., Fritz, K. P., Neugebauer, H., Sariciftci, N. S., Kumar, S., & Scholes, G. D. (2007). Hybrid solar cells using PbS nanoparticles. *Solar Energy Materials and solar cells, 91*(5), 420-423.

Gupta, D., Mukhopadhyay, S., & Narayan, K. (2010). Fill factor in organic solar cells. *Solar Energy Materials and solar cells, 94*(8), 1309-1313.

Halls, J., & Friend, R. (1997). The photovoltaic effect in a poly (p-phenylenevinylene)/perylene heterojunction. *Synthetic Metals, 85*(1-3), 1307-1308.

Hamadani, B. H., & Dougherty, B. (2016). Solar cell characterization. In *Semiconductor Materials for Solar Photovoltaic Cells* (pp. 229-245). Springer.

Hammond, M. R., Kline, R. J., Herzing, A. A., Richter, L. J., Germack, D. S., Ro, H.-W., Soles, C. L., Fischer, D. A., Xu, T., & Yu, L. (2011). Molecular order in high-efficiency polymer/fullerene bulk heterojunction solar cells. *ACS nano, 5*(10), 8248-8257.

Han, P., Viterisi, A., Ferre-Borrull, J., Pallarés, J., & Marsal, L. (2017). Morphology-driven photocurrent enhancement in PTB7/PC71BM bulk heterojunction solar cells via the use of ternary solvent processing blends. *Organic Electronics, 41*, 229-236.

He, Z., Zhong, C., Huang, X., Wong, W. Y., Wu, H., Chen, L., Su, S., & Cao, Y. (2011). Simultaneous enhancement of open-circuit voltage, short-circuit current density, and fill factor in polymer solar cells. *Advanced materials, 23*(40), 4636-4643.

He, Z., Zhong, C., Su, S., Xu, M., Wu, H., & Cao, Y. (2012). Enhanced power-conversion efficiency in polymer solar cells using an inverted device structure. *Nature Photonics, 6*(9), 591-595.

Hedley, G. J., Ward, A. J., Alekseev, A., Howells, C. T., Martins, E. R., Serrano, L. A., Cooke, G., Ruseckas, A., & Samuel, I. D. (2013). Determining the optimum morphology in high-performance polymer-fullerene organic photovoltaic cells. *Nature communications, 4*(1), 1-10.

Hegedus, S., & Luque, A. (2011). Achievements and challenges of solar electricity from photovoltaics. *Handbook of photovoltaic science and engineering*, 1-38.

Heiman, D. (2004). Photoluminescence spectroscopy. *Physics U600, Adv Lab I—Physics of Waves and Optics—Summer*.

Holliday, S., Ashraf, R. S., Wadsworth, A., Baran, D., Yousaf, S. A., Nielsen, C. B., Tan, C.-H., Dimitrov, S. D., Shang, Z., & Gasparini, N. (2016). High-efficiency and air-stable P3HT-based polymer solar cells with a new non-fullerene acceptor. *Nature communications, 7*(1), 1-11.

Hou, C., Yu, H., & Huang, C. (2019). Solution-processable Ti 3 C 2 T x nanosheets as an efficient hole transport layer for high-performance and stable polymer solar cells. *Journal of Materials Chemistry C, 7*(37), 11549-11558.

Hou, J., & Guo, X. (2013). Active layer materials for organic solar cells. In *Organic solar cells* (pp. 17-42). Springer.

Hu, X., Wang, M., Huang, F., Gong, X., & Cao, Y. (2013). 23% enhanced efficiency of polymer solar cells processed with 1-chloronaphthalene as the solvent additive. *Synthetic Metals, 164*, 1-5.

Hu, Z., Zhang, J., Hao, Z., & Zhao, Y. (2011). Influence of doped PEDOT: PSS on the performance of polymer solar cells. *Solar Energy Materials and solar cells, 95*(10), 2763-2767.

Huang, D., Li, Y., Xu, Z., Zhao, S., Zhao, L., & Zhao, J. (2015). Enhanced performance and morphological evolution of PTB7: PC 71 BM polymer solar cells by using solvent mixtures with different additives. *Physical Chemistry Chemical Physics, 17*(12), 8053-8060.

Huang, Y.-C., Hsu, J.-H., Liao, Y.-C., Yen, W.-C., Li, S.-S., Lin, S.-T., Chen, C.-W., & Su, W.-F. (2011). Employing an amphiphilic interfacial modifier to enhance the performance of a poly (3-hexyl thiophene)/TiO 2 hybrid solar cell. *Journal of Materials Chemistry, 21*(12), 4450-4456.

Hussain, A. A., Pal, A. R., & Patil, D. S. (2014). High photosensitivity with enhanced photoelectrical contribution in hybrid nanocomposite flexible UV photodetector. *Organic Electronics, 15*(9), 2107-2115.

Hwang, I., McNeill, C. R., & Greenham, N. C. (2014). Evolution of phase separation upon annealing and the influence on photocurrent generation in ternary blend organic solar cells. *Synthetic Metals, 189*, 63-68.

Ikram, M., Ali, S., Murray, R., Hussain, A., & Shah, S. I. (2015). Influence of fullerene derivative replacement with TiO2 nanoparticles in organic bulk heterojunction solar cells. *Current Applied Physics, 15*(1), 48-54.

Intemann, J. J., Yao, K., Li, Y. X., Yip, H. L., Xu, Y. X., Liang, P. W., Chueh, C. C., Ding, F. Z., Yang, X., & Li, X. (2014). Highly Efficient Inverted Organic Solar Cells Through Material and Interfacial Engineering of Indacenodithieno [3, 2-

b] thiophene-Based Polymers and Devices. *Advanced Functional Materials, 24*(10), 1465-1473.

Ishii, M., Mori, T., Fujikawa, H., Tokito, S., & Taga, Y. (2000). Improvement of organic electroluminescent device performance by in situ plasma treatment of indium–tin-oxide surface. *Journal of Luminescence, 87*, 1165-1167.

Jørgensen, M., Carlé, J. E., Søndergaard, R. R., Lauritzen, M., Dagnæs-Hansen, N. A., Byskov, S. L., Andersen, T. R., Larsen-Olsen, T. T., Böttiger, A. P., & Andreasen, B. (2013). The state of organic solar cells—A meta analysis. *Solar Energy Materials and solar cells, 119*, 84-93.

Jørgensen, M., Norrman, K., Gevorgyan, S. A., Tromholt, T., Andreasen, B., & Krebs, F. C. (2012). Stability of polymer solar cells. *Advanced materials, 24*(5), 580-612.

Jørgensen, M., Norrman, K., & Krebs, F. C. (2008). Stability/degradation of polymer solar cells. *Solar Energy Materials and solar cells, 92*(7), 686-714.

Jung, E. H., Jeon, N. J., Park, E. Y., Moon, C. S., Shin, T. J., Yang, T.-Y., Noh, J. H., & Seo, J. (2019). Efficient, stable and scalable perovskite solar cells using poly (3-hexylthiophene). *Nature, 567*(7749), 511-515.

Kalinin, S. V., & Gruverman, A. (2010). *Scanning probe microscopy of functional materials: nanoscale imaging and spectroscopy*. Springer Science & Business Media.

Karagiannidis, P., Kassavetis, S., Pitsalidis, C., & Logothetidis, S. (2011). Thermal annealing effect on the nanomechanical properties and structure of P3HT: PCBM thin films. *Thin Solid Films, 519*(12), 4105-4109.

Kettle, J., Waters, H., Horie, M., & Chang, S. (2012). Effect of hole transporting layers on the performance of PCPDTBT: PCBM organic solar cells. *Journal of Physics D: Applied Physics, 45*(12), 125102.

Kietzke, T. (2007). Recent advances in organic solar cells. *Advances in OptoElectronics, 2007*.

Kim, G.-H., Song, H.-K., & Kim, J. Y. (2011). The effect of introducing a buffer layer to polymer solar cells on cell efficiency. *Solar Energy Materials and solar cells, 95*(4), 1119-1122.

Kim, J. T., Lee, J., Jang, S., Yu, Z., Park, J. H., Jung, E. D., Lee, S., Song, M. H., Whang, D. R., & Wu, S. (2020). Solution processable small molecules as efficient electron transport layers in organic optoelectronic devices. *Journal of Materials Chemistry A, 8*(27), 13501-13508.

Kim, J. Y., Kim, S. H., Lee, H. H., Lee, K., Ma, W., Gong, X., & Heeger, A. J. (2006). New architecture for high-efficiency polymer photovoltaic cells using solution-based titanium oxide as an optical spacer. *Advanced materials, 18*(5), 572-576.

Kim, J. Y., Lee, K., Coates, N. E., Moses, D., Nguyen, T.-Q., Dante, M., & Heeger, A. J. (2007). Efficient tandem polymer solar cells fabricated by all-solution processing. *Science, 317*(5835), 222-225.

Kim, K.-D., Lim, D. C., Seo, H. O., Lee, J. Y., Seo, B. Y., Lee, D. J., Song, Y., Cho, S., Lim, J.-H., & Kim, Y. D. (2013). Enhanced performance of organic photovoltaics by TiO2-interlayer with precisely controlled thickness between ZnO electron collecting and active layers. *Applied Surface Science, 279*, 380-383.

Kim, W., Kim, J. K., Kim, E., Ahn, T. K., Wang, D. H., & Park, J. H. (2015). Conflicted effects of a solvent additive on PTB7: PC71BM bulk heterojunction solar cells. *The Journal of Physical Chemistry C, 119*(11), 5954-5961.

Kim, Y., Ballantyne, A. M., Nelson, J., & Bradley, D. D. (2009). Effects of thickness and thermal annealing of the PEDOT: PSS layer on the performance of polymer solar cells. *Organic Electronics, 10*(1), 205-209.

Kirchartz, T., Pieters, B. E., Kirkpatrick, J., Rau, U., & Nelson, J. (2011). Recombination via tail states in polythiophene: fullerene solar cells. *Physical Review B, 83*(11), 115209.

Krebs, F. C., Gevorgyan, S. A., & Alstrup, J. (2009). A roll-to-roll process to flexible polymer solar cells: model studies, manufacture and operational stability studies. *Journal of Materials Chemistry, 19*(30), 5442-5451.

Kumar, A., Bansal, A., Behera, B., Jain, S. L., & Ray, S. S. (2016). Ternary hybrid polymeric nanocomposites through grafting of polystyrene on graphene oxide-TiO2 by surface initiated atom transfer radical polymerization (SI-ATRP). *Materials Chemistry and Physics, 172*, 189-196.

Kumar, V., Sharma, D., Sharma, K., & Dwivedi, D. (2016). Structural, optical and electrical characterization of vacuum-evaporated nanocrystalline CdSe thin films for photosensor applications. *Applied Physics A, 122*(11), 1-6.

Kuo, C.-Y., Su, M.-S., Chen, G.-Y., Ku, C.-S., Lee, H.-Y., & Wei, K.-H. (2011). Annealing treatment improves the morphology and performance of photovoltaic devices prepared from thieno [3, 4-c] pyrrole-4, 6-dione-based donor/acceptor conjugated polymers and CdSe nanostructures. *Energy & Environmental Science, 4*(6), 2316-2322.

Leo, K. (2016). *Elementary Processes in Organic Photovoltaics* (Vol. 272). Springer.

Li, W., Liu, Z., Yang, R., Guan, Q., Jiang, W., Islam, A., Lei, T., Hong, L., Peng, R., & Ge, Z. (2017). High-performance polymer solar cells employing rhodamines as cathode interfacial layers. *ACS applied materials & interfaces, 9*(32), 27083-27089.

Liang, Y., Xu, Z., Xia, J., Tsai, S. T., Wu, Y., Li, G., Ray, C., & Yu, L. (2010). For the bright future—bulk heterojunction polymer solar cells with power conversion efficiency of 7.4%. *Advanced materials, 22*(20), E135-E138.

Lim, S. P., Lim, Y. S., Pandikumar, A., Lim, H. N., Ng, Y. H., Ramaraj, R., Bien, D. C. S., Abou-Zied, O. K., & Huang, N. M. (2017). Gold–silver@ TiO 2 nanocomposite-modified plasmonic photoanodes for higher efficiency dye-sensitized solar cells. *Physical Chemistry Chemical Physics, 19*(2), 1395-1407.

Lin, R., Wright, M., Veettil, B. P., & Uddin, A. (2014). Enhancement of ternary blend organic solar cell efficiency using PTB7 as a sensitizer. *Synthetic Metals, 192*, 113-118.

Liu, C.-Y., Holman, Z. C., & Kortshagen, U. R. (2009). Hybrid solar cells from P3HT and silicon nanocrystals. *Nano letters, 9*(1), 449-452.

Liu, D., & Kelly, T. L. (2014). Perovskite solar cells with a planar heterojunction structure prepared using room-temperature solution processing techniques. *Nature Photonics, 8*(2), 133-138.

Liu, F., Shao, S., Guo, X., Zhao, Y., & Xie, Z. (2010). Efficient polymer photovoltaic cells using solution-processed MoO3 as anode buffer layer. *Solar Energy Materials and solar cells, 94*(5), 842-845.

Liu, L.-q., Wang, Z.-x., Zhang, H.-q., & Xue, Y.-c. (2010). Solar energy development in China—A review. *Renewable and Sustainable Energy Reviews, 14*(1), 301-311.

Liu, Q., Jiang, Y., Jin, K., Qin, J., Xu, J., Li, W., Xiong, J., Liu, J., Xiao, Z., & Sun, K. (2020). 18% Efficiency organic solar cells. *Science Bulletin, 65*(4), 272-275.

Liu, S., Yuan, J., Deng, W., Luo, M., Xie, Y., Liang, Q., Zou, Y., He, Z., Wu, H., & Cao, Y. (2020). High-efficiency organic solar cells with low non-radiative recombination loss and low energetic disorder. *Nature Photonics, 14*(5), 300-305.

Liu, Z., Chen, Q., Hong, Z., Zhou, H., Xu, X., De Marco, N., Sun, P., Zhao, Z., Cheng, Y.-B., & Yang, Y. (2016). Low-temperature TiO x compact layer for planar heterojunction perovskite solar cells. *ACS applied materials & interfaces, 8*(17), 11076-11083.

Lu, H., Ma, Y., Gu, B., Tian, W., & Li, L. (2015). Identifying the optimum thickness of electron transport layers for highly efficient perovskite planar solar cells. *Journal of Materials Chemistry A, 3*(32), 16445-16452.

Lu, L., Xu, T., Chen, W., Landry, E. S., & Yu, L. (2014). Ternary blend polymer solar cells with enhanced power conversion efficiency. *Nature Photonics, 8*(9), 716-722.

Lu, L., Xu, T., Jung, I. H., & Yu, L. (2014). Match the interfacial energy levels between hole transport layer and donor polymer to achieve high solar cell performance. *The Journal of Physical Chemistry C, 118*(40), 22834-22839.

Lüer, L., Egelhaaf, H.-J., Oelkrug, D., Cerullo, G., Lanzani, G., Huisman, B.-H., & De Leeuw, D. (2004). Oxygen-induced quenching of photoexcited states in polythiophene films. *Organic Electronics, 5*(1-3), 83-89.

Ma, W., Yang, C., Gong, X., Lee, K., & Heeger, A. J. (2005). Thermally stable, efficient polymer solar cells with nanoscale control of the interpenetrating network morphology. *Advanced Functional Materials, 15*(10), 1617-1622.

MacDonald, G. A., Veneman, P. A., Placencia, D., & Armstrong, N. R. (2012). Electrical property heterogeneity at transparent conductive oxide/organic semiconductor interfaces: Mapping contact ohmicity using conducting-tip atomic force microscopy. *ACS nano, 6*(11), 9623-9636.

Mahmoudi, T., Wang, Y., & Hahn, Y.-B. (2018). Graphene and its derivatives for solar cells application. *Nano Energy, 47*, 51-65.

Matsui, T., Bidiville, A., Maejima, K., Sai, H., Koida, T., Suezaki, T., Matsumoto, M., Saito, K., Yoshida, I., & Kondo, M. (2015). High-efficiency amorphous silicon solar cells: impact of deposition rate on metastability. *Applied Physics Letters, 106*(5), 053901.

Mauer, R., Howard, I. A., & Laquai, F. (2010). Effect of nongeminate recombination on fill factor in polythiophene/methanofullerene organic solar cells. *The Journal of Physical Chemistry Letters, 1*(24), 3500-3505.

McGehee, M. D., & Topinka, M. A. (2006). Pictures from the blended zone. *Nature materials, 5*(9), 675-676.

Meng, L., Zhang, Y., Wan, X., Li, C., Zhang, X., Wang, Y., Ke, X., Xiao, Z., Ding, L., & Xia, R. (2018). Organic and solution-processed tandem solar cells with 17.3% efficiency. *Science, 361*(6407), 1094-1098.

Mizuno, Y., King, F., Yamauchi, Y., Homma, T., Tanaka, A., Takakuwa, Y., & Momose, T. (2002). Temperature dependence of oxide decomposition on titanium surfaces in ultrahigh vacuum. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 20*(5), 1716-1721.

Mohapatra, S. K., Misra, M., Mahajan, V. K., & Raja, K. S. (2007). Design of a highly efficient photoelectrolytic cell for hydrogen generation by water splitting: Application of TiO2-x C x nanotubes as a photoanode and Pt/TiO2 nanotubes as a cathode. *The Journal of Physical Chemistry C, 111*(24), 8677-8685.

Moiz, S. A., Khan, I. A., Younis, W. A., & Karimov, K. S. (2016). Space charge–limited current model for polymers. *Conducting Polymers, 5*, 91.

Mola, G. T., Dlamini, W. E., & Oseni, S. O. (2016). Improving optical absorption bandwidth using bi-layer bulkheterojunction organic photoactive medium. *Journal of Materials Science: Materials in Electronics, 27*(11), 11628-11633.

Moon, J. S., Jo, J., & Heeger, A. J. (2012). Nanomorphology of PCDTBT: PC70BM bulk heterojunction solar cells. *Advanced Energy Materials, 2*(3), 304-308.

Muhammad, F. F., Karim Sangawi, A. W., Hashim, S., Ghoshal, S., Abdullah, I. K., & Hameed, S. S. (2019). Simple and efficient estimation of photovoltaic cells and modules parameters using approximation and correction technique. *PloS one, 14*(5), e0216201.

Muhammad, F. F., Ketuly, K. A., & Yahya, M. Y. (2018). Effect of thermal annealing on a ternary organic solar cell incorporating Gaq3 organometallic as a boosting acceptor. *Journal of Inorganic and Organometallic Polymers and Materials, 28*(1), 102-109.

Muhammad, F. F., Muhammad, A. J., & Sulaiman, K. (2016). Optical response and photovoltaic performance of organic solar cells based on dh6t: alq3 active layer. *Journal of Technology Innovations in Renewable Energy, 5*(1), 3.

Muhammad, F. F., & Sulaiman, K. (2018). Thermal stability and reproducibility enhancement of organic solar cells by Tris (hydroxyquinoline) gallium dopant forming a dual acceptor active layer. *ARO-The Scientific Journal of Koya University, 6*(2), 69-78.

Muhammad, F. F., Yahya, M. Y., Hameed, S. S., Aziz, F., Sulaiman, K., Rasheed, M. A., & Ahmad, Z. (2017). Employment of single-diode model to elucidate the variations in photovoltaic parameters under different electrical and thermal conditions. *PloS one, 12*(8), e0182925.

Muhammad, F. F., Yahya, M. Y., & Sulaiman, K. (2017). Improving the performance of solution-processed organic solar cells by incorporating small molecule acceptors into a ternary bulk heterojunction based on DH6T: Mq3: PCBM (M= Ga, Al). *Materials Chemistry and Physics, 188*, 86-94.

Muhammadsharif, F. F., Hashim, S., Hameed, S. S., Ghoshal, S., Abdullah, I. K., Macdonald, J., & Yahya, M. Y. (2019). Brent's algorithm based new computational approach for accurate determination of single-diode model parameters to simulate solar cells and modules. *Solar Energy, 193*, 782-798.

Nakamura, M., Yamaguchi, K., Kimoto, Y., Yasaki, Y., Kato, T., & Sugimoto, H. (2019). Cd-free Cu (In, Ga)(Se, S) 2 thin-film solar cell with record efficiency of 23.35%. *IEEE Journal of Photovoltaics, 9*(6), 1863-1867.

Namkoong, G., Kong, J., Samson, M., Hwang, I.-W., & Lee, K. (2013). Active layer thickness effect on the recombination process of PCDTBT: PC71BM organic solar cells. *Organic Electronics, 14*(1), 74-79.

O'Regan, B., Veenstra, S., Verhees, W., Kroon, J., Sommeling, P., Bakker, K., & Smit, H. (2005). Recombination kinetics of interpenetrating heterojunctions: comparison of dye sensitized and polymer solar cells. Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005.,

Ochiai, S., Imamura, S., Kannappan, S., Palanisamy, K., & Shin, P.-K. (2013). Characteristics and the effect of additives on the nanomorphology of PTB7/PC71BM composite films. *Current Applied Physics, 13*, S58-S63.

Olejníček, J., Šmíd, J., Čada, M., Kšírová, P., Kohout, M., Perekrestov, R., Tvarog, D., Kment, Š., Kmentová, H., & Hubička, Z. (2020). High rate deposition of photoactive TiO2 films by hot hollow cathode. *Surface and Coatings Technology, 383*, 125256.

Omrane, B., Landrock, C., Chuo, Y., Hohertz, D., Aristizabal, J., Kaminska, B., & Kavanagh, K. (2011). Long-lasting flexible organic solar cells stored and tested entirely in air. *Applied Physics Letters, 99*(26), 283.

Padinger, F., Rittberger, R. S., & Sariciftci, N. S. (2003). Effects of postproduction treatment on plastic solar cells. *Advanced Functional Materials, 13*(1), 85-88.

Park, S. H., Roy, A., Beaupre, S., Cho, S., Coates, N., Moon, J. S., Moses, D., Leclerc, M., Lee, K., & Heeger, A. J. (2009). Bulk heterojunction solar cells with internal quantum efficiency approaching 100%. *Nature Photonics, 3*(5), 297-302.

Peumans, P., Yakimov, A., & Forrest, S. R. (2003). Small molecular weight organic thin-film photodetectors and solar cells. *Journal of applied physics, 93*(7), 3693-3723.

Po, R., Carbonera, C., Bernardi, A., & Camaioni, N. (2011). The role of buffer layers in polymer solar cells. *Energy & Environmental Science, 4*(2), 285-310.

Proctor, C. M., & Nguyen, T.-Q. (2015). Effect of leakage current and shunt resistance on the light intensity dependence of organic solar cells. *Applied Physics Letters, 106*(8), 23_21.

Qi, B., & Wang, J. (2013). Fill factor in organic solar cells. *Physical Chemistry Chemical Physics, 15*(23), 8972-8982.

Rao, K. G., Ashok, C., Rao, K. V., Chakra, C. S., & Rajendar, V. (2014). Green Synthesis of TiO2 Nanoparticles Using Hibiscus Flower Extract. Conference ICEMS,

Richardson, B. J., Zhu, L., & Yu, Q. (2013). Inverted hybrid solar cells based on pyrite FeS2 nanocrystals in P3HT: PCBM with enhanced photocurrent and air-stability. *Solar Energy Materials and solar cells, 116*, 252-261.

Rivaton, A., Chambon, S., Manceau, M., Gardette, J.-L., Lemaître, N., & Guillerez, S. (2010). Light-induced degradation of the active layer of polymer-based solar cells. *Polymer Degradation and Stability, 95*(3), 278-284.

Rocha, F. S., Gomes, A. J., Lunardi, C. N., Kaliaguine, S., & Patience, G. S. (2018). Experimental methods in chemical engineering: Ultraviolet visible spectroscopy—UV-Vis. *The Canadian Journal of Chemical Engineering, 96*(12), 2512-2517.

Ryu, M. S., Cha, H. J., & Jang, J. (2010). Effects of thermal annealing of polymer: fullerene photovoltaic solar cells for high efficiency. *Current Applied Physics, 10*(2), S206-S209.

Sai, H., Matsui, T., Kumagai, H., & Matsubara, K. (2018). Thin-film microcrystalline silicon solar cells: 11.9% efficiency and beyond. *Applied Physics Express, 11*(2), 022301.

Salamandra, L., La Notte, L., Fazolo, C., Di Natali, M., Penna, S., Mattiello, L., Cinà, L., Del Duca, R., & Reale, A. (2020). A comparative study of organic photodetectors based on P3HT and PTB7 polymers for visible light communication. *Organic Electronics, 81*, 105666.

Salim, T., Yin, Z., Sun, S., Huang, X., Zhang, H., & Lam, Y. M. (2011). Solution-processed nanocrystalline TiO2 buffer layer used for improving the performance of organic photovoltaics. *ACS applied materials & interfaces, 3*(4), 1063-1067.

Sánchez, J., Balderrama, V., Estrada, M., Osorio, E., Ferré-Borrull, J., Marsal, L., & Pallarès, J. (2017). Stability study of high efficiency polymer solar cells using TiOx as electron transport layer. *Solar Energy, 150*, 147-155.

Sariciftci, N. S., Braun, D., Zhang, C., Srdanov, V., Heeger, A. J., Stucky, G., & Wudl, F. (1993). Semiconducting polymer-buckminsterfullerene heterojunctions: Diodes, photodiodes, and photovoltaic cells. *Applied Physics Letters, 62*(6), 585-587.

Savikhin, V., Jagadamma, L. K., Purvis, L. J., Robertson, I., Oosterhout, S. D., Douglas, C. J., Samuel, I. D., & Toney, M. F. (2018). Morphological, chemical, and electronic changes of the conjugated polymer PTB7 with thermal annealing. *IScience, 2*, 182-192.

Shaheen, S. E., Brabec, C. J., Sariciftci, N. S., Padinger, F., Fromherz, T., & Hummelen, J. C. (2001). 2.5% efficient organic plastic solar cells. *Applied Physics Letters, 78*(6), 841-843.

Shalan, A. E., Narra, S., Oshikiri, T., Ueno, K., Shi, X., Wu, H.-P., Elshanawany, M. M., Diau, E. W.-G., & Misawa, H. (2017). Optimization of a compact layer of TiO 2 via atomic-layer deposition for high-performance perovskite solar cells. *Sustainable Energy & Fuels, 1*(7), 1533-1540.

Sharenko, A., Kuik, M., Toney, M. F., & Nguyen, T. Q. (2014). Crystallization-Induced Phase Separation in Solution-Processed Small Molecule Bulk Heterojunction Organic Solar Cells. *Advanced Functional Materials, 24*(23), 3543-3550.

Sharma, N., Gupta, S. K., & Negi, C. M. S. (2019). Influence of active layer thickness on photovoltaic performance of PTB7: PC70BM bulk heterojunction solar cell. *Superlattices and Microstructures, 135*, 106278.

Sharma, R., Bhalerao, S., & Gupta, D. (2016). Effect of incorporation of CdS NPs on performance of PTB7: PCBM organic solar cells. *Organic Electronics, 33*, 274-280.

Sharma, R., Lee, H., Gupta, V., Kim, H., Kumar, M., Sharma, C., Chand, S., Yoo, S., & Gupta, D. (2016). Photo-physics of PTB7, PCBM and ICBA based ternary solar cells. *Organic Electronics, 34*, 111-117.

Skompska, M. (2010). Hybrid conjugated polymer/semiconductor photovoltaic cells. *Synthetic Metals, 160*(1-2), 1-15.

Spanggaard, H., & Krebs, F. C. (2004). A brief history of the development of organic and polymeric photovoltaics. *Solar Energy Materials and solar cells, 83*(2-3), 125-146.

Spieß, L., Behnken, H., Genzel, C., Schwarzer, R., & Teichert, G. (2009). *Moderne röntgenbeugung* (Vol. 2). Springer.

Sun, Y., Chien, S.-C., Yip, H.-L., Zhang, Y., Chen, K.-S., Zeigler, D. F., Chen, F.-C., Lin, B., & Jen, A. K.-Y. (2011). Chemically doped and cross-linked hole-transporting materials as an efficient anode buffer layer for polymer solar cells. *Chemistry of Materials, 23*(22), 5006-5015.

Sun, Y., Wang, M., Liu, C., Li, Z., Fu, D., & Guo, W. (2020). Realizing efficiency improvement of polymer solar cells by using multi-functional cascade electron transport layers. *Organic Electronics, 76*, 105482.

Supasai, T., Amornkitbamrung, V., Thanachayanont, C., Tang, I.-M., Sutthibutpong, T., & Rujisamphan, N. (2017). Visualizing nanoscale phase morphology for understanding photovoltaic performance of PTB7: PC71BM solar cell. *Applied Surface Science, 422*, 509-517.

Tada, K. (2015). Thermally robust bulk heterojunction photocells based on PTB7: C70 composites. *Solar Energy Materials and solar cells, 132*, 15-20.

Tang, C. W. (1986). Two-layer organic photovoltaic cell. *Applied Physics Letters, 48*(2), 183-185.

Terzano, R., Denecke, M. A., Falkenberg, G., Miller, B., Paterson, D., & Janssens, K. (2019). Recent advances in analysis of trace elements in environmental samples by X-ray based techniques (IUPAC Technical Report). *Pure and Applied Chemistry, 91*(6), 1029-1063.

Titus, D., Samuel, E. J. J., & Roopan, S. M. (2019). Nanoparticle characterization techniques. In *Green synthesis, characterization and applications of nanoparticles* (pp. 303-319). Elsevier.

To, C. H., Ng, A., Dong, Q., Djurišić, A. B., Zapien, J. A., Chan, W. K., & Surya, C. (2015). Effect of PTB7 properties on the performance of PTB7: PC71BM solar cells. *ACS applied materials & interfaces, 7*(24), 13198-13207.

Upama, M. B., Wright, M., Puthen-Veettil, B., Elumalai, N. K., Mahmud, M. A., Wang, D., Chan, K. H., Xu, C., Haque, F., & Uddin, A. (2016). Analysis of burn-in photo degradation in low bandgap polymer PTB7 using photothermal deflection spectroscopy. *RSC advances, 6*(106), 103899-103904.

Vijay, P., & Sumaria, V. (2014). Advancement in P3HT PCBM solar cells, the most efficient Polymer Photovoltaic cell. 10th Annual Sesion of Students' Chemical Engineering Congress (SCHEMCON),

Waldauf, C., Schilinsky, P., Hauch, J., & Brabec, C. J. (2004). Material and device concepts for organic photovoltaics: towards competitive efficiencies. *Thin Solid Films, 451*, 503-507.

Wan, Q., Guo, X., Wang, Z., Li, W., Guo, B., Ma, W., Zhang, M., & Li, Y. (2016). 10.8% efficiency polymer solar cells based on PTB7-Th and PC71BM via binary solvent additives treatment. *Advanced Functional Materials, 26*(36), 6635-6640.

Wang, G., Jiu, T., Tang, G., Li, J., Li, P., Song, X., Lu, F., & Fang, J. (2014). Interface modification of ZnO-based inverted PTB7: PC71BM organic solar cells by cesium stearate and simultaneous enhancement of device parameters. *ACS Sustainable Chemistry & Engineering, 2*(5), 1331-1337.

Wang, H., Huang, J., Xing, S., & Yu, J. (2016). Improved mobility and lifetime of carrier for highly efficient ternary polymer solar cells based on TIPS-pentacene in PTB7: PC71BM. *Organic Electronics, 28*, 11-19.

Wang, J., & Lin, Z. (2010). Dye-sensitized TiO2 nanotube solar cells with markedly enhanced performance via rational surface engineering. *Chemistry of Materials, 22*(2), 579-584.

Wang, L., Zhao, S., Xu, Z., Zhao, J., Huang, D., & Zhao, L. (2016). Integrated effects of two additives on the enhanced performance of PTB7: PC71BM polymer solar cells. *Materials, 9*(3), 171.

Wang, M., Xie, F., Xie, W., Zheng, S., Ke, N., Chen, J., Zhao, N., & Xu, J. (2011). Device lifetime improvement of polymer-based bulk heterojunction solar cells by incorporating copper oxide layer at Al cathode. *Applied Physics Letters, 98*(18), 88.

Wang, Z., Zhang, F., Li, L., An, Q., Wang, J., & Zhang, J. (2014). The underlying reason of DIO additive on the improvement polymer solar cells performance. *Applied Surface Science, 305*, 221-226.

Wetzelaer, G., Kuik, M., Lenes, M., & Blom, P. (2011). Origin of the dark-current ideality factor in polymer: fullerene bulk heterojunction solar cells. *Applied Physics Letters, 99*(15), 153506.

Wright, M., & Uddin, A. (2012). Organic—inorganic hybrid solar cells: A comparative review. *Solar Energy Materials and solar cells, 107*, 87-111.

Wu, J., Lan, Z., Lin, J., Huang, M., Huang, Y., Fan, L., Luo, G., Lin, Y., Xie, Y., & Wei, Y. (2017). Counter electrodes in dye-sensitized solar cells. *Chemical Society Reviews, 46*(19), 5975-6023.

Wu, Q., Bhattacharya, M., Moore, L. M., & Morgan, S. E. (2014). Air processed P3HT: PCBM photovoltaic cells: Morphology correlation to annealing, degradation, and recovery. *Journal of Polymer Science Part B: Polymer Physics, 52*(23), 1511-1520.

Würfel, P. (2007). Photovoltaic principles and organic solar cells. *CHIMIA International Journal for Chemistry, 61*(12), 770-774.

Xing, G., Mathews, N., Sun, S., Lim, S. S., Lam, Y. M., Grätzel, M., Mhaisalkar, S., & Sum, T. C. (2013). Long-range balanced electron-and hole-transport lengths in organic-inorganic CH3NH3PbI3. *Science, 342*(6156), 344-347.

Xue, J., & Forrest, S. R. (2004). Carrier transport in multilayer organic photodetectors: II. Effects of anode preparation. *Journal of applied physics, 95*(4), 1869-1877.

Yang, X., & Uddin, A. (2014). Effect of thermal annealing on P3HT: PCBM bulk-heterojunction organic solar cells: A critical review. *Renewable and Sustainable Energy Reviews, 30*(C), 324-336.

Yin, B., Liu, Q., Yang, L., Wu, X., Liu, Z., Hua, Y., Yin, S., & Chen, Y. (2010). Buffer layer of PEDOT: PSS/graphene composite for polymer solar cells. *Journal of nanoscience and nanotechnology, 10*(3), 1934-1938.

Yonezawa, K., Kamioka, H., Yasuda, T., Han, L., & Moritomo, Y. (2013). Exciton-to-carrier conversion processes in a low-band-gap organic photovoltaic. *Japanese Journal of Applied Physics, 52*(6R), 062405.

Yu, H., Huang, X., Li, Y., & Wu, Z. (2017). Effect of methanol treatment on the performance of P3HT: PC 71 BM bulk heterojunction solar cells with various cathodes. *Journal of Materials Science: Materials in Electronics, 28*(17), 12909-12915.

Yu, Z., Zhang, L., Tian, S., Zhang, F., Zhang, B., Niu, F., Zeng, P., Qu, J., Rudd, P. N., & Huang, J. (2018). Hot-Substrate Deposition of Hole-and Electron-Transport Layers for Enhanced Performance in Perovskite Solar Cells. *Advanced Energy Materials, 8*(2), 1701659.

Yuan, J., Zhang, Y., Zhou, L., Zhang, G., Yip, H.-L., Lau, T.-K., Lu, X., Zhu, C., Peng, H., & Johnson, P. A. (2019). Single-junction organic solar cell with over 15% efficiency using fused-ring acceptor with electron-deficient core. *Joule, 3*(4), 1140-1151.

Yun, T. W., & Sulaiman, K. (2011). Fabrication and morphological characterization of hybrid polymeric solar cells based on P3HT and inorganic nanocrystal blends. *Sains Malaysiana, 40*(1), 43-47.

Zhang, F., Gadisa, A., Inganäs, O., Svensson, M., & Andersson, M. R. (2004). Influence of buffer layers on the performance of polymer solar cells. *Applied Physics Letters, 84*(19), 3906-3908.

Zhang, F., Zhuo, Z., Zhang, J., Wang, X., Xu, X., Wang, Z., Xin, Y., Wang, J., Wang, J., & Tang, W. (2012). Influence of PC60BM or PC70BM as electron acceptor on the performance of polymer solar cells. *Solar Energy Materials and solar cells, 97*, 71-77.

Zhang, W., Zhao, B., He, Z., Zhao, X., Wang, H., Yang, S., Wu, H., & Cao, Y. (2013). High-efficiency ITO-free polymer solar cells using highly conductive PEDOT: PSS/surfactant bilayer transparent anodes. *Energy & Environmental Science, 6*(6), 1956-1964.

Zhang, Y., Dang, X. D., Kim, C., & Nguyen, T. Q. (2011). Effect of charge recombination on the fill factor of small molecule bulk heterojunction solar cells. *Advanced Energy Materials, 1*(4), 610-617.

Zhang, Y., Li, X., Dai, T., Xu, D., Xi, J., & Chen, X. (2019). Charge transport and extraction of PTB7: PC 71 BM organic solar cells: effect of film thickness and thermal-annealing. *RSC advances, 9*(43), 24895-24903.

Zhao, D., Tan, S., Ke, L., Liu, P., Kyaw, A., Sun, X., Lo, G., & Kwong, D. (2010). Optimization of an inverted organic solar cell. *Solar Energy Materials and solar cells, 94*(6), 985-991.

Zhao, X., Xiang, J., Liu, D., Zhou, D., Wang, G., Zhou, G., Alameh, K., Ding, B., & Song, Q. (2016). Impact of alkyl chain length of 1, n-diiodoalkanes on PC71BM distribution in both bulk and air surface of PTB7: PC71BM film. *Organic Electronics, 37*, 358-365.

Zheng, Y., Li, S., Zheng, D., & Yu, J. (2014). Effects of different polar solvents for solvent vapor annealing treatment on the performance of polymer solar cells. *Organic Electronics, 15*(11), 2647-2653.

Zhong, Y., Suzuki, K., Inoue, D., Hashizume, D., Izawa, S., Hashimoto, K., Koganezawa, T., & Tajima, K. (2016). Interface-induced crystallization and nanostructure formation of [6, 6]-phenyl-C 61-butyric acid methyl ester (PCBM) in polymer blend films and its application in photovoltaics. *Journal of Materials Chemistry A, 4*(9), 3335-3341.

Zhou, H., Zhang, Y., Seifter, J., Collins, S. D., Luo, C., Bazan, G. C., Nguyen, T. Q., & Heeger, A. J. (2013). High-efficiency polymer solar cells enhanced by solvent treatment. *Advanced materials, 25*(11), 1646-1652.

Zhu, L., Zhang, M., Zhou, G., Hao, T., Xu, J., Wang, J., Qiu, C., Prine, N., Ali, J., & Feng, W. (2020). Efficient organic solar cell with 16.88% efficiency enabled by refined acceptor crystallization and morphology with improved charge transfer and transport properties. *Advanced Energy Materials, 10*(18), 1904234.

LIST OF PUBLICATIONS

Al-Shekaili, N., Hashim, S., Muhammadsharif, F. F., MZ, A.-A., Sulaiman, K., Yahya, M. Y., & Ahmad, M. R. (2020). Enhanced Performance of PTB7: PC71BM Based Organic Solar Cells by Incorporating a Nano-Layered Electron Transport of Titanium Oxide. *ECS Journal of Solid State Science and Technology, 9*(10), 105003.

Al-Shekaili, N., Hashim, S., Muhammadsharif, F. F., Al-Abri, M., Sulaiman, K., Yahya, M. Y., & Ahmed, M. R. (2021). The impact of TiO_2 nanostructures on the physical properties and electrical performance of organic solar cells based on PTB7: PC71BM bulk heterojunctions. *Materials Today: Proceedings, 42*, 1921-1927.

Al-Shekaili, N., Hashim, S., Muhammadsharif, F.F. *et al.* Efficiency and Stability Improvement of Organic Solar Cells Based on PTB7: PCBM Through Hot-Substrate Coating. *J. Electron. Mater.* (2021).