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Organic Semi-transparent Photovoltaics for Energy Efficient Buildings

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Abstract

Recent progress in bulk heterojunction organic photovoltaics (OPVs) is approaching the milestone of 20% in power conversion efficiency (PCE) by utilising novel non-fullerene acceptors (NFAs). In comparison to the traditional fullerene acceptors, the NFA acceptors have simpler synthetic methods, a suitable band gap that increases the overall active layer absorption, and tunable energy levels that favour the open-circuit voltage.

Organic solar cells based on NFAs have boosted the efficiency of OPVs to over 17%, while significant improvements in device stability have also been reported. The progress of NFAs provides commercialization opportunities for printed and highly transparent and efficient OPVs, which enables the application of this technology in various niche markets.

This thesis focuses on the progress of energy-efficient buildings, the importance of conventional Si-based photovoltaics for energy-efficient buildings, and finally, the potential of emerging semitransparent OPVs for building-integrated photovoltaics (BIPVs) and other applications. The experimental work presented in this thesis involves the development and fabrication of semitransparent OPVs and the evaluation of their electrical and optical performance for BIPV applications. The design of semitransparent OPVs is challenging due to the requirement for high transparency and efficiency. The thesis demonstrates the use of high-performance NFAs in a ternary fullerene blend and evaluates their efficiency on the basis of BIPV applications.

Finally, the thesis concludes with a discussion of the potential applications of semitransparent OPVs. The literature and the experimental results suggest that semitransparent OPVs have the potential to provide a viable solution for energy-efficient buildings and other sectors where both visible light transmission and electricity generation are required. Overall, this study contributes to the field of semitransparent OPVs and provides a foundation for future research in this area.

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Dedication

This thesis is dedicated to my parents for their unwavering love and support and for always encouraging me to follow my dreams and pursue my goals.

Nomenclature

Acronyms

ADR	Aperiodic Dielectric Reflectors
Agri-PV	Agrivoltaics: Photovoltaics applicable in agriculture
AM1.5G	Air-mass 1.5 Global Tilted Irradiance
ARC	Antireflection Coatings
AVT	Average Visible Transmittance
BIPVs	Building Integrated Photovoltaics
BM	Black Matte
CCT	Correlated Colour Temperature
CIE	Commission Internationale de l'Eclairage
CRI	Colour Rendering Index
CVD	Chemical Vapour Deposition
DMD	Dielectric/ Metal/ Dielectric Electrode
DSSCs	Dye-Sensitised Solar Cells
EEB	Energy Efficient Buildings
EED	Energy Efficiency Directive
EQE	External Quantum Efficiency
ETL	Electron Transport Layer
GHG	Greenhouse Gas
HOMO	Highest Occupied Molecular Orbit
HTL	Hole Transport Layer
IEA	International Energy Agency
IoT	Internet of Things
LUE	Light-Utilization Efficiency
LUMO	Lowest Unoccupied Molecular Orbit
NFAs	Non-fullerene Acceptors
NIR	Near-Infrared Electromagnetic Radiation
NREL	The National Renewable Energy Laboratory

nZEB	Nearly-Zero Energy Buildings
OPVs	Organic Photovoltaics
PCE	Power Conversion Efficiency
PVs	Photovoltaics
QUE	Quantum-Utilization Efficiency
R2R	Roll-to-Roll
R&D	Research and Development
ST-OPVs	Semi-transparent Organic Photovoltaics
TF-PVs	Thin-film Photovoltaics
TPVs	Transparent Photovoltaics
UV	Ultraviolet Electromagnetic Radiation

Chemical Compounds

a-Si	Amorphous Silicon
ACS8	Indacenodithiophene (IDT) as core, alkylthio-substituted thiophene as π-bridge and electron withdrawing 3-(1,1-dicyanomethylene)-5,6-difluoro-1-indanone (IC2F) as end groups
Ag	Silver
AgNWs	Silver Nanowires
AZO	Aluminium-doped ZnO
BT-CIC	(4,4,10,10-tetrakis (4-hexylphenyl)-5,11-(2-ethylhexyloxy)-4,10-dihydro-dithienyl[1,2-b:4,5b'] benzodi-thiophene-2,8-diyl)bis(2-(3-oxo-2,3-dihydroinden-5,6-dichloro-1-ylidene)malononitrile))
C_{60}-SAM	4-(1',5'-Dihydro-1'-methyl-2'H-[5,6]fullereno-C60-Ih-[1,9-c]pyrrol-2'-yl)benzoic acid
CB	Chlorobenzene
CdTe	Cadmium Telluride
CF	Chloroform
CIGS	Copper Indium Gallium Selenide
CN	1-chloronaphthalene
CNT	Carbon Nanotubes
DTY6	2,2'-((2Z,2'Z)-((12,13-bis(2-decylteradecyl)-3,9-diundecyl-12,13-dihydro-[1,2,5] thiadiazolo[3,4-e]thieno[2",3":4',5']thieno[2',3':4,5]pyrrolo[3,2-g]thieno[2',3':4,5]thieno[3,2-b]indole-2,10-diyl) bis(methanylylidene))bis(5,6-difluoro-3-oxo-2,3-dihydro-1H-indene-2,1-diylidene))dimalononitrile (BTP-4F-24)
FNIC1	Benzo[1,2-b:4,5-b']dithieno[3,2-b]thiophene
FNIC2	Thieno[3,2-b]thiophene-fused benzo-[1,2-b:4,5-b']dithiophene
FTO	Fluorine doped Tin Oxide
GO	Graphene Oxide
GZO	Gallium-doped ZnO
IEICO-4F	2,2'-((2Z,2'Z)-(((4,4,9,9-tetrakis(4-hexylphenyl)-4,9-dihydro-sindaceno[1,2-b:5,6-b']dithiophene-2,7-diyl)bis(4-((2-ethylhexyl)oxy)thiophene-5,2-diyl))bis(methanylylidene))bis(5,6-difluoro-3-oxo-2,3-dihydro-1H-indene-2,1- diylidene))dimalononitrile

IHIC	2,2'-[[4,4,9,9-tetrakis(4-hexylphenyl)-4,9-dihydrothieno[3',2':4,5]cyclopenta[1,2-b]thieno[2",3":3',4'] cyclopenta[1',2':4,5]thieno[2,3- d]thiophene-2,7-diyl]bis [methylidyne(3-oxo-1H-indene-2,1(3H)-diylidene)]]bis
IPA	Isopropanol
IT-4F	3,9-bis(2-methylene-((3-(1,1-dicyanomethylene)-6,7-difluoro)-indanone))-5,5,11,11-tetrakis(4-hexylphenyl)-dithieno[2,3-d:2',3'-d']-s-indaceno[1,2-b:5,6-b']dithiophene
ITIC	3,9-bis(2-methylene-(3-(1,1-dicyanomethylene)indanone))-5,5,11,11-tetrakis(4-hexylphenyl) dithieno[2,3-d:2',3'-d']-s-indaceno[1,2-b:5,6-b']-dithiophene
ITO	Indium Tin Oxide
J52	Poly[4,8-bis[5-(2-ethylhexyl)thiophen-2-yl]benzo[1,2-b:4,5-b']dithiophene-5,5'-diyl-alt-4,7-bis(thien-2-yl)-5,6-difluoro-2-(2-hexyldecyl)-2H-benzo[d][1,2,3]triazole]
J71	Poly[[5,6-difluoro-2-(2-hexyldecyl)-2H-benzotriazole-4,7-diyl]-2,5-thiophenediyl[4,8-bis[5-(tripropylsilyl)-2-thienyl]benzo[1,2-b:4,5-b']dithiophene-2,6-diyl]-2,5-thiophenediyl]
LiF/Al	Lithium Fluoride/ Aluminum
MoO_3	Molybdenum Trioxide
NSM	2-[4-(carboxyl)benzylidene]-1H-indene-1,3(2H)-dione
p-Si	Polycrystalline Silicon
P3HT	Poly(3-hexylthiophene)
PBDB-T	Poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b:4,5-b']-dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione))]
PBDTT-DPP	Poly(2,60-4,8-bis(5-ethylhexylthienyl)benzo-[1,2-b;3,4-b]dithiophene-alt-5-dibutyloctyl-3,6-bis(5-bromothiophen-2-yl)pyrrolo[3,4-c]pyrrole-1,4-dione)
PBDTTT-EFT	Poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b;4,5-b0]dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno[3,4-b]thiophene-)-2-carboxylate-2-6-diyl)]
$PC_{61}BM$	[6,6]-phenyl-C_{61}-butyric acid methyl ester
$PC_{71}BM$	[6,6]-Phenyl-C_{71}-butyric acid methyl ester
PCDTBT	Poly[N-900-hepta-decanyl-2,7-carbazole-alt-5,5-(40,70-di-2-thienyl-20,10,30-benzothiadiazole)
PDIN	N,N'-bis(3-(dimethylamino)propyl)perylene-3,4,9,10-tetracarboxylic diimide
PDINO	N,N'-bis(N,N-dimethylpropan-1-amine oxide)perylene-3,4,9,10-tetracarboxylic diimide
PDMS	Polydimethylsiloxane
PEDOT	Poly(3,4-ethylenedioxythiophene)
PFN	Poly[(9,9-bis(3'-(N,N-dimethylamino)propyl)-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)]
PFN-Br	Poly(9,9-bis(3'-(N,N-dimethyl)-N-ethylammoinium-propyl-2,7-fluorene)-alt-2,7-(9,9-dioctylfluorene)) dibromide
PIDT-PhanQ	Poly(indacenodithiophene-co-phenanthro[9,10-b]quinoxaline)
PM6	Poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-fluoro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione)]
PM7	Poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-chloro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione)]
PMA	Phosphomolybdic acid

PMMA	Poly(methyl methacrylate)
PN	1-phenylnaphthalene
PSBTBT	Poly[(4,4-bis(2-ethylhexyl)-dithieno[3,2-b:2',3'-d]silole)-2,6-diyl-alt-(2,1,3-benzothiadiazole)-4,7-diyl]
PSS	Polystyrene sulfonate
PTB7	Polythieno[3,4-b]-thiophene/benzodithiophene
PTB7-Th	Poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b;4,5-b']dithiophene-2,6-diyl-alt-(4-(2-ethylhexyl)-3-fluorothieno[3,4-b]thiophene-)-2-carboxylate-2-6-diyl)]
PtNP	Platinum Nanoparticles
SnO_2	Tin Oxide
T1	Poly[(2,6-(4,8-bis(5-(2-ethylhexyl-3-fluoro)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione)]-ran-poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-benzo[1,2-b:4,5-b']dithiophene))-alt-(2,2-ethyl-3(or4)-carboxylate-thiophene)](PBDB-TF-T1)
TT-FIC	(4,4,10,10-tetrakis(4-hexylphenyl)-4,10-dihydrothieno [2",3":4',5'] thieno[3',2':4,5]cyclopenta[1,2-b]thieno[2,3-d]thiophene-2,8-diyl)bis(2-(3-oxo-2,3-dihydroinden-5,6-difluoro-1-ylidene)malononitrile)
WO_3	Tungsten Trioxide
Y6	2,2'-((2Z,2'Z)-((12,13-bis(2-ethylhexyl)-3,9-diundecyl-12,13-dihydro-[1,2,5]thiadiazolo[3,4-e] thieno[2",3":4',5']thieno[2',3':4,5]pyrrolo[3,2-g]thieno[2',3':4,5]thieno[3,2-b]indole-2,10-diyl) bis(methanylylidene))bis(5,6-difluoro-3-oxo-2,3-dihydro-1H-indene-2,1-diylidene))dimalononitrile
ZnO	Zinc Oxide

Symbols

$\alpha(\lambda)$	Action Spectrum
γ	Photon
λ	Wavelength
$\overline{x}$, $\overline{y}$, $\overline{z}$	Colour-Matching Functions
$A(\lambda)$	Absorbance
G	Crops Growth Factor
J_{MP}	Current Density at Maximum Power
J_{SC}	Short-circuit Current Density
$R(\lambda)$	Reflectance
$S(\lambda)$	Solar Irradiance
$T(\lambda)$	Transmittance
$V(\lambda)$	Photopic Response
V_{MP}	Voltage at Maximum Power
V_{OC}	Open-circuit Voltage
FF	Fill Factor

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Chapter 1

Introduction

As a looming crisis, global warming is expected to worsen the challenges humanity is currently facing with the rapid and appalling climatic changes around the globe. Generally, one of the major energy-consuming industries is the building and construction industry. The building sector, which is also responsible for up to 40% of the total carbon emissions, accounts for about 36% of the total energy consumed globally [7].

Energy has a significant and direct impact on the socioeconomic aspects of emerging and developing countries. Rising energy prices have recently increased pressure on consumers. Unfairly, the cost of energy falls heaviest on those who can least afford it. The poorest 20% of households in developed nations use only a third of the energy compared to the richest 20%, but they allocate a much larger percentage of their income to cover their basic needs. As a result, energy poverty has become a major issue in many developing countries in recent years [8].

However, over the last two decades, the average efficiency of the building stock has increased, causing residential energy density demand to drop. More specifically, according to the IEA 2022 report, despite the overall increase in residential energy use, the energy consumption per floor space recorded a reduction from 0.83 GJ/m^2 in 2000 to 0.59 GJ/m^2 in 2019 [8]. Even though the amount of floor space in developing countries is increasing, it is evident that the improvement in the efficiency of buildings counters the amount of excess energy demand [8].

The world is making significant efforts to speed up investments in building efficiency and increase the deployment rate of building retrofits, but much more innovation will be required to create more efficient and cost-effective clean energy technologies and bring us closer to achieving net zero emissions by 2050. R&D is becoming more crucial in both the private and public sectors [8]. This is especially true when it comes to developing energy projects and technologies that have lower initial costs than their conventional counterparts.

In 2022, at the Annual Global Conference on Energy Efficiency, IEA members and governments around the world acknowledged the implications of import dependence, addressed the high cost of energy, and pledged new funding to help combat the energy crisis by implementing new action plans focusing on energy efficiency policies. Regarding the regulations of the building industry, targeted funding models were set to achieve the milestones for 2030, which include the retrofitting of 2.5% of the existing building stock each year and ensuring the carbon neutrality of new buildings. The electrification of buildings through the necessary energy efficiency measures is a long-term target with the objective of further reducing residential carbon emissions, assuming that the supply should be provided by renewable energy sources by 2050 [9].

As a result of the aforementioned consequences, alternative energy sources will need to be gradually adapted into the global energy mix due to the foreseeable rapid increase in energy consumption among the growing population. Incorporating and expanding access to affordable and reliable technologies can help accomplish the desired sustainable development goals and counter socioeconomic inequality [7].

1.1 Problem Statement

With photovoltaic technology, sunlight can be converted directly into electricity, which has been considered a viable and long-term answer to the population's growing energy needs. However, despite the advantages of photovoltaic technology, the implementation of traditional opaque solar panels in the building sector has been limited by aesthetic and practical concerns, which have hindered their widespread adoption. To address these concerns, researchers have been developing transparent solar cells that can be integrated into windows and other building materials, allowing for a more seamless and visually appealing integration of solar technology into buildings. This could potentially increase the adoption of solar energy in the building sector.

1.2 Purpose and Scope

The aim of this thesis is twofold. Firstly, as introduced above, it aims to analyse the current challenges facing the building energy sector in reducing the energy demand of buildings to acceptable levels during the electrification process. This includes examining the limitations of traditional energy-efficient building design and retrofitting measures as well as exploring potential technological solutions that could increase and further support the on-site generation of renewable energy supply. By doing so, this thesis seeks to contribute to the broader goal of achieving a more sustainable and carbon-neutral built environment.

Secondly, the thesis research continues with laboratory trials for the fabrication and evaluation of semi-transparent photovoltaics, predominantly for window applications in the building sector. Building-integrated photovoltaic (BIPV) systems have emerged as a promising solution to the challenge of seamlessly integrating solar cells into building façades, roofs, and windows. Among the various types of BIPV technologies, semi-transparent organic photovoltaics (ST-OPVs) have garnered attention for their potential to combine high efficiency with attractive visual properties. However, the development of semi-transparent OPVs for building applications is still in its early stages, and there are several technical and practical challenges that need to be addressed.

Therefore, this thesis will focus on the fabrication and characterization of semi-transparent OPVs and the evaluation of their performance for BIPV applications. The research will involve the optimisation of materials, device architecture, and processing techniques to achieve high power conversion efficiency while maintaining reasonably high levels of transparency. Overall,