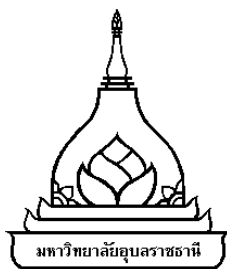


**NOVEL BENZOCHROMENE AND THIOARENE
FOR ORGANIC ELECTRONIC DEVICES**

THIKHAMPORN UPPALABAT

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE
MAJOR IN CHEMISTRY
FACULTY OF SCIENCE
UBON RATCHATHANI UNIVERSITY
ACADEMIC YEAR 2018
COPYRIGHT OF UBON RATCHATHANI UNIVERSIT**



UBON RATCHATHANI UNIVERSITY
THESIS APPROVAL
MASTER OF SCIENCE
MAJOR IN CHEMISTRY FACULTY OF SCIENCE

TITLE NOVEL BENZOCHROMENE AND THIOARENE FOR ORGANIC
ELECTRONIC DEVICES

AUTHOR MISS THIKHAMPORN UPPALBAT

EXAMINATION COMMITTEE

DR. SOMBOON SAHASITHIWAT	CHAIRPERSON
ASST. PROF. DR. RUKKIAT JITCHATI	MEMBER
ASST. PROF. DR. KITTIYA WONGKHAN	MEMBER

ADVISORS

.....
(ASST. PROF. DR. RUKKIAT JITCHATI)

.....
(ASST. PROF. DR. CHARIDA PUKAHUTA)
DEAN, FACULTY OF SCIENCE

.....
(ASSOC. PROF. DR. ARIYAPORN PONGRAT)
VICE PRESIDENT FOR ACADEMIC AFFAIRS

COPYRIGHT OF UBON RATCHATHANI UNIVERSITY
ACADEMIC YEAR 2018

ACKNOWLEDGEMENTS

Firstly, I would like to thank my advisor; Asst. Prof. Dr. Rukkiat Jitchati for his guidance and encouragement. He has truly shared his generously valuable time and expertise to provide insight and constructive suggestions throughout the course of this work. The help has enabled me to carry out my work successfully. Many thank to Asst. Prof. Dr. Kittiya Wongkhan for her comments and suggestions in completion of the thesis.

I also would like to thank Dr. Somboon Sahasithiwat and Mrs. Laongdao Kangkeaw from National Metal and Materials Technology Center (MTEC) for their content advice and sharing their extensive knowledge about the fabrication of OLEDs and OFETs device. I would like to acknowledge the Organometallic and Catalytic Center (OCC), Department of Chemistry, Faculty of Science, Ubon Ratchathani University for the synthesis facilities. I am grateful to the financial support from the Science Achievement Scholarship of Thailand (SAST) for providing all laboratory facilities.

Finally, I must express my deepest gratitude to my family for their always encouraged me to pursue my goals, always succeed, and never admit defeat. Thanks everyone in the RJ & KW group for contributed and helped me to make this research work possible at Ubon Ratchathani University.

Thikhamporn Uppalabat
Researcher

บทคัดย่อ

เรื่อง : สารเบนโซโครมีนและไทโอเอรีนชนิดใหม่สำหรับอุปกรณ์อิเล็กทรอนิกส์ชนิดสารอินทรีย์

ผู้วิจัย : ทิฆัมพร อุปลาบัติ

ชื่อปริญญา : วิทยาศาสตร์มหาบัณฑิต

สาขาวิชา : เคมี

อาจารย์ที่ปรึกษา: ผู้ช่วยศาสตราจารย์ ดร. รักเกียรติ จิตคตติ

คำสำคัญ : ไดโอดเปล่งแสงชนิดสารอินทรีย์, ทรานซิสเตอร์สนามไฟฟ้าชนิดสารอินทรีย์, เบนโซโครมีน, ไทโอเอรีน, ระบบไฟคอนจูเกต

การออกแบบและพัฒนาโครงสร้างสารอินทรีย์ด้วยระบบไฟ-คอนจูเกตกำลังเป็นที่ได้รับความสนใจอย่างกว้างขวาง เพื่อใช้เป็นวัสดุในชิ้นงานอุปกรณ์อิเล็กทรอนิกส์ชนิดสารอินทรีย์ อาทิ อุปกรณ์ไดโอดเปล่งแสงชนิดสารอินทรีย์ และอุปกรณ์ทรานซิสเตอร์สนามไฟฟ้าชนิดสารอินทรีย์ เป็นต้น ในการวิจัยนี้ได้ทำการสังเคราะห์ไฟ-คอนจูเกตของอนุพันธ์เบนโซโครมีน (ARAR2 และ ARAR3) และอนุพันธ์ไทโอเอรีน (ARTH2, ARTH3 และ THTH2) ผ่านปฏิกิริยาคู่ควบโซโนกาซิระ ปฏิกิริยาคู่ควบโดยตรง ปฏิกิริยาการปิดวงด้วยโลหะรูทีเนียม และปฏิกิริยาสกอลล์ ตามลำดับ ซึ่งสารโมเลกุลเป้าหมายทั้งหมดถูกนำไปพิสูจน์เอกลักษณ์ด้วย ^1H NMR, ^{13}C NMR, FT-IR และแมส สเปกโตรสโคปี นอกจากนี้สาร ARTH2 ยังถูกยืนยันโครงสร้างทางเคมีด้วย 2D NMR (เทคนิค COSY และ HMBC) สำหรับการศึกษาคุณสมบัติทางแสงของสารโมเลกุลเป้าหมาย พบว่าสารทั้งหมดเกิดการคายแสงในช่วงของแสงสีเขียวผ่านกระบวนการการคายแสงแบบฟลูออเรสเซนซ์ จากนั้นทำการศึกษาคูสมบัติทางความร้อนของสารโมเลกุลเป้าหมาย พบว่าสารที่เป็นอนุพันธ์ของไทโอเอรีน (ARTH2, ARTH3 และ THTH2) จะมีเสถียรภาพทางความร้อนสูง หลังจากนั้นสารโมเลกุลเป้าหมายทั้งหมดถูกนำไปศึกษาประสิทธิภาพการเป็นชิ้นงานอุปกรณ์ไดโอดเปล่งแสงชนิดสารอินทรีย์ โดยใช้โครงสร้างเป็น ITO/NPB/MADN: 20 %wt ของสารโมเลกุลเป้าหมาย/Bphen/LiF/Al พบว่าสาร ARTH2 ให้ประสิทธิภาพที่ดีที่สุดและคายแสงในช่วงของแสงสีเขียวเหลือง ด้วยค่าการเปล่งแสงสูงสุดเท่ากับ $4,699 \text{ cd/m}^2$ ค่าประสิทธิภาพเชิงกระแสและค่าประสิทธิภาพเชิงกำลังไฟฟ้าเท่ากับ 2.71 cd/A และ 0.79 Lm/W ตามลำดับ นอกจากนี้สารโมเลกุลเป้าหมายทั้งหมดยังถูกนำไปศึกษาประสิทธิภาพการเป็นชิ้นงานอุปกรณ์ทรานซิสเตอร์สนามไฟฟ้าชนิดสารอินทรีย์ ซึ่งพบว่าสาร THTH2 แสดงคุณสมบัติการเป็นทรานซิสเตอร์ชนิดบวกด้วยค่าสภาพคล่องทางไฟฟ้าเท่ากับ $1.64 \times 10^{-2} \text{ cm}^2/\text{Vs}$ และอัตราส่วนกระแสไฟฟ้าเปิดและปิดเท่ากับ 6.48

ABSTRACT

TITLE : NOVEL BENZOCHROMENE AND THIOARENE FOR ORGANIC ELECTRONIC DEVICES
AUTHOR : THIKHAMPORN UPPALABAT
DEGREE : MASTER OF SCIENCE
MAJOR : CHEMISTRY
ADVISOR : ASST. PROF. RUKKIAT JITCHATI, Ph. D.
KEYWORDS : ORGANIC LIGHT EMITTING DIODES (OLEDs), ORGANIC FIELD EFFECT TRANSISTORS (OFETs), BENZOCHROMENE, THIOARENE, *PI*-CONJUGATED SYSTEM

Design and development of the organic structures with π -conjugated system were interested for using in electronic device such as organic light emitting diodes (OLEDs) and organic field effect transistors (OFETs). In this work, we synthesized π -conjugated of benzochromene (**ARAR2** and **ARAR3**) and thioarene (**ARTH2**, **ARTH3** and **THTH2**) derivatives via Sonogashira coupling, direct cross-coupling, ruthenium cyclization and Scholl reactions, respectively. All target compounds were characterized by ^1H NMR, ^{13}C NMR, FT-IR and mass spectroscopy. Moreover, the chemical structure of **ARTH2** was clearly characterized by 2D NMR (COSY and HMBC spectroscopy). The photophysical properties of target compounds showed photoluminescence emission which appeared in range of green regions with fluorescence process. The **ARTH2**, **ARTH3** and **THTH2** which are thioarene products showed a high thermal stability. After that, all target compounds were studied OLED performance by using the structure of ITO/NPB/MADN: 20 %wt of targeted compounds/Bphen/LiF/Al. The results indicated that **ARTH2** showed the best performance and exhibited yellowish green colour with maximum luminance at 4,699 cd/m^2 , current and power efficiencies at 2.71 cd/A and 0.79 Lm/W , respectively. In addition, the target compounds were investigated in OFETs. It was found that **THTH2** showed the p-type character with hole mobility of $1.64 \times 10^{-2} \text{ cm}^2/\text{Vs}$ and on/off current ratio of 6.48.

CONTENTS

	PAGE
ACKNOWLEDGEMENTS	I
THAI ABSTRACT	II
ENGLISH ABSTRACT	III
CONTENTS	IV
LIST OF SCHEMES	VI
LIST OF TABLES	VII
LIST OF FIGURES	VIII
LIST OF APPREVIATIONS	XV
CHAPTER 1 INTRODUCTION	
1.1 Organic light emitting diodes (OLEDs)	3
1.2 Organic field effect transistors (OFETs)	9
1.3 Objectives of thesis	12
CHAPTER 2 LITERATURE REVIEWS	13
CHAPTER 3 EXPERIMENTAL	21
3.1 Chemicals	21
3.2 Instruments	23
3.3 Synthesis	26
3.4 OLEDs device fabrication	34
3.5 OFETs device fabrication	37
CHAPTER 4 RESULTS AND DISCUSSIONS	
4.1 Synthesis and reaction mechanism	41
4.2 Characterization and structure identification	49
4.3 Photophysical study	61
4.4 Electrochemical study	68
4.5 Thermal study	71
4.6 OLEDs performance	72
4.7 OFETs performance	76

CONTENTS (CONTINUED)

	PAGE
CHAPTER 5 CONCLUSIONS	79
REFERENCES	81
APPENDICES	
A Characterized data	89
B Photophysical and electrochemical data	106
C Device performance data	120
D Publication	134
CURRICULUM VITAE	139

LIST OF SCHEMES

SCHEME		PAGES
4.1	The synthetic pathway for the target molecules	41
4.2	The conditions for used synthesis	42
4.3	Sonogashira reaction mechanism for ARAR1 , ARTH1 and TH1	43
4.4	Synthesis pathway for THTH1	44
4.5	Direct cross-coupling reaction mechanism for THTH1 and THTH1/1	45
4.6	Synthesis pathways for ARAR2 , ARTH2 and THTH2	46
4.7	Ruthenium cyclization reaction mechanism for ARAR2 , ARTH2 and THTH2	47
4.8	Synthesis pathways for ARAR3 and ARTH3	48
4.9	Scholl reaction mechanism for ARAR3 and ARTH3	48

LIST OF TABLES

TABLE		PAGES
3.1	Chemicals for the synthesis	21
3.2	Chemicals for OLEDs performance study	22
3.3	Chemicals for OFETs performance study	23
3.4	Instruments for the molecular characterization	23
3.5	Instruments for OLEDs study	24
3.6	Instruments for OFETs study	24
3.7	The optimization of intramolecular Scholl reaction	28
4.1	FT-IR characterization of all targeted	58
4.2	Characterization and structure identification for all compounds	59
4.3	The maximum absorption wavelengths of products in toluene solution	62
4.4	Photoluminescence characteristics of all products in toluene solution	67
4.5	Electrochemical property and energy levels of products	70
4.6	The optimization of OLEDs device fabrication	72
4.7	Summary of OLEDs performances of target compounds with configuration of ITO/NPB(30nm)/MADN: Dopant(20 %wt, 40nm)/Bphen(30nm)/LiF(0.5nm)/Al(100nm)	75
4.8	Summary of OFETs device performances with configurations of the materials investigated in this work	78

LIST OF FIGURES

FIGURE		PAGES
1.1	Examples of small organic molecules	1
1.2	Examples of organic polymeric molecules	2
1.3	Example of OLED displays	3
1.4	The multi-layer OLED structures	4
1.5	Schematic energy diagram of basic process in multi-layer OLED	4
1.6	Jablonski energy diagram	5
1.7	Electronic processes of host-guest molecules	6
1.8	Energy level relationship in guest-host systems	7
1.9	Luminance, current density and turn on voltage characteristic	7
1.10	The CIE 1931 color space chromaticity diagram	8
1.11	Examples of OFET in the future	9
1.12	OFET device configuration of bottom-gate-top-contact	9
1.13	Schematic description of the principle of operation for OFET	10
1.14	Threshold voltage, transfer curve and on/off current characteristics	11
1.15	Output characteristic	12
2.1	Benzo[<i>d,e</i>]chromene derivatives synthesis from iridium catalyst by Yan and co-worker	13
2.2	Benzo[<i>d,e</i>]chromene derivatives synthesis from rhodium catalyst by Wang and co-worker	14
2.3	Benzo[<i>d,e</i>]chromene derivatives synthesis from rhodium catalyst by Miura and co-worker	14
2.4	Benzo[<i>d,e</i>]chromene derivatives synthesis from rhodium catalyst by Tan and co-worker	14
2.5	Benzo[<i>d,e</i>]chromene derivatives synthesis from ruthenium catalyst by Xie and co-worker	15

LIST OF FIGURES (CONTINUED)

FIGURE		PAGES
2.6	Benzo[<i>d,e</i>]chromene derivatives synthesis from ruthenium catalyst by Thirunavukkarasu and co-worker	15
2.7	The structures and emission spectra of benzo[<i>d,e</i>]chromene derivatives by Mochida and co-worker	16
2.8	Benzo[<i>d,e</i>]chromene derivatives for OLEDs device by Miss Benjawan Somchob and co-worker	16
2.9	Thioarene derivatives synthesis from AlCl ₃ catalyst by Badger and co-worker	17
2.10	Thioarene derivatives synthesis from FeCl ₃ catalyst by Larsen and co-worker	17
2.11	Thioarene derivatives synthesis from FeCl ₃ catalyst by Jian and co-worker	18
2.12	The structure and photophysical property of thioarene derivatives by Daniel and co-worker	18
2.13	Thioarene derivatives for OFETs device by Lui and co-worker	19
2.14	Thioarene derivatives for OFETs device by Katz and co-workers	19
2.15	Thioarene derivatives for OFETs device by Yanming and co-worker	19
2.16	Thioarene derivatives for OFETs device by Takimiya and co-worker	20
2.17	Thioarene derivatives for OFETs device by Yamamoto and co-worker	20
3.1	Cleaning process of ITO substrate	35
3.2	Coating process of organic thin film	36
3.3	Coating process of cathode electrode	36
3.4	Cleaning process of Si/SiO ₂ substrate	38
3.5	Coating process of organic thin film	39

LIST OF FIGURES (CONTINUED)

FIGURE		PAGES
3.6	Coating process of source-drain-gate electrodes	39
4.1	Molecular structures of the target compounds	40
4.2	¹ H NMR in CDCl ₃ and the assignment of ARAR1	49
4.3	¹ H NMR in CDCl ₃ and the assignment of ARTH1	50
4.4	¹ H NMR in CDCl ₃ and the assignment of TH1	51
4.5	¹ H NMR in CDCl ₃ of mixed THTH1 and THTH1/1	52
4.6	¹³ C NMR in CDCl ₃ and the assignment of THTH1 and THTH1/1	53
4.7	¹ H NMR in CDCl ₃ and the assignment of five target products	54
4.8	¹³ C NMR in CDCl ₃ and the assignment of all target products	55
4.9	COSY spectrum in CDCl ₃ and the relation of ARTH2	56
4.10	HMBC spectrum in CDCl ₃ and the relation of ARTH2	57
4.11	UV-Visible absorption spectra of target products	62
4.12	UV-Visible absorption spectra and structures of ARAR2 and ARTH2	63
4.13	UV-Visible absorption spectra and structures of ARTH2 and THTH2	64
4.14	UV-Visible absorption spectra and structures of ARAR2 and ARAR3	65
4.15	UV-Visible absorption spectra and structures of ARAR3 and ARTH3	66
4.16	Photoluminescence spectra of target products	67
4.17	All target products in solid state (top) and solution (below) under UV lamp	68
4.18	Cyclic voltammogram of target products reported compared with ferrocene/ferrocenium ion	69
4.19	Schematic HOMO and LUMO levels of target products	70

LIST OF FIGURES (CONTINUED)

FIGURE		PAGES
4.20	TGA curves of target products	71
4.21	OLEDs device configuration (upper left), the relative HOMO and LUMO energy levels of the materials investigated in this work (upper right) and structures of NPB, MADN and Bphen (bottom)	73
4.22	Current density and luminance versus applied bias voltage of the device structure ITO/NPB(30nm)/MADN: Dopant(20 % wt, 40nm)/Bphen(30nm)/LiF(0.5nm)/ Al(100nm)	74
4.23	The relative HOMO and LUMO energy levels of ARTH2 device	75
4.24	CIE coordinates and emission colour for OLED devices of target compounds	76
4.25	OFETs device configuration in this work	77
4.26	Transfer curve (left) and output curve (right) of pentacene	77
4.27	Transfer curve (left) and output curve (right) of THTH2	78
A.1	¹ H NMR in CDCl ₃ and the assignment of ARAR2 , ARTH2 and THTH2	90
A.2	¹ H NMR in CDCl ₃ and the assignment of ARAR2 and ARAR3	90
A.3	¹ H NMR in CDCl ₃ and the assignment of ARTH2 and ARTH3	91
A.4	¹³ C NMR in CDCl ₃ and the assignment of ARAR2 , ARTH2 and THTH2	91
A.5	¹³ C NMR in CDCl ₃ and the assignment of ARAR2 and ARAR3	92
A.6	¹³ C NMR in CDCl ₃ and the assignment of ARTH2 and ARTH3	92
A.7	Mass spectra and the assignment of ARAR1	93
A.8	Mass spectra and the assignment of ARTH1	94

LIST OF FIGURES (CONTINUED)

FIGURE		PAGES
A.9	Mass spectra and the assignment of TH1	95
A.10	Mass spectra and the assignment of THTH1	96
A.11	Mass spectra and the assignment of THTH1/1	97
A.12	Mass spectra and the assignment of ARAR2	98
A.13	Mass spectra and the assignment of ARTH2	99
A.14	Mass spectra and the assignment of THTH2	100
A.15	Mass spectra and the assignment of ARAR3	101
A.16	Mass spectra and the assignment of ARTH3	102
A.17	FT-IR spectra and the assignment of ARAR2	103
A.18	FT-IR spectra and the assignment of ARTH2	103
A.19	FT-IR spectra and the assignment of THTH2	104
A.20	FT-IR spectra and the assignment of ARAR3	104
A.21	FT-IR spectra and the assignment of ARTH3	105
A.22	UV-Visible absorption spectra of all products	107
A.23	Lifetime spectra of ARAR2	109
A.24	Lifetime spectra of ARTH2	109
A.25	Lifetime spectra of THTH2	110
A.26	Lifetime spectra of ARAR3	110
A.27	Lifetime spectra of ARTH3	111
A.28	Fluorescence quantum yield spectra of ARAR2	111
A.29	Fluorescence quantum yield spectra of ARTH2	112
A.30	Fluorescence quantum yield spectra of THTH2	112
A.31	Fluorescence quantum yield spectra of ARAR3	113
A.32	Fluorescence quantum yield spectra of ARTH3	113
A.33	Cyclic voltammogram of ferrocene in acetonitrile	114
A.34	Reduction potentials of ARAR2 in acetonitrile	115
A.35	Reduction potentials of ARTH2 in acetonitrile	116

LIST OF FIGURES (CONTINUED)

FIGURE	PAGES	
A.36	Reduction potentials of THTH2 in acetonitrile	117
A.37	Reduction potentials of ARAR3 in acetonitrile	118
A.38	Reduction potentials of ARTH3 in acetonitrile	119
A.39	OLEDs device fabrication and energy level diagram of ARAR2	121
A.40	Current density and luminance versus applied bias voltage (left) and current and power efficiencies (right) of ARAR2 device	121
A.41	PL, EL, CIE coordinate and emission colour of ARAR2 device	122
A.42	OLEDs device fabrication and energy level diagram of ARTH2	122
A.43	Current density and luminance versus applied bias voltage (left) and current and power efficiencies (right) of ARTH2 device	123
A.44	PL, EL, CIE coordinate and emission colour of ARTH2 device	123
A.45	OLEDs device fabrication and energy level diagram of THTH2	124
A.46	Current density and luminance versus applied bias voltage (left) and current and power efficiencies (right) of THTH2 device	124
A.47	PL, EL, CIE coordinate and emission colour of THTH2 device	125
A.48	OLEDs device fabrication and energy level diagram of ARAR3	125
A.49	Current density and luminance versus applied bias voltage (left) and current and power efficiencies (right) of ARAR3 device	126
A.50	PL, EL, CIE coordinate and emission colour of ARAR3 device	126

LIST OF FIGURES (CONTINUED)

FIGURE		PAGES
A.51	OLEDs device fabrication and energy level diagram of ARTH3	127
A.52	Current density and luminance versus applied bias voltage (left) and current and power efficiencies (right) of ARTH3 device	127
A.53	PL, EL, CIE coordinate and emission colour of ARTH3 device	128
A.54	Transfer curve at gate-source voltage 10 to -60 V of pentacene	129
A.55	Transfer curve (left) and output curve (right) of pentacene	129
A.56	Transfer curve at gate-source voltage 10 to -60 V of ARAR2	130
A.57	Transfer curve at gate-source voltage 10 to -60 V of ARTH2	130
A.58	Transfer curve at gate-source voltage 10 to -100 V of THTH2	131
A.59	Transfer curve (left) and output curve (right) of THTH2	131
A.60	Transfer curve at gate-source voltage 10 to -60 V of ARAR3	132
A.61	Transfer curve at gate-source voltage 10 to -60 V of ARTH3	133

LIST OF ABBREVIATIONS

ABBREVIATION	FULL WORD
AIE	Aggregation-induced emission
A	Ampere
Å	Angstrom
br	Broad
cd	Candela
C_i	Capacitance per unit area of the gate dielectric layer
^{13}C NMR	Carbon nuclear magnetic resonance spectroscopy
cm	Centimeter
L	Channel length
W	Channel width
δ	Chemical shift
CIE	Commission internationale de l'éclairage
COSY	Correlation spectroscopy
C	Coulomb
J	Coupling constant
J	Current density
J - V - L	Current density-voltage-luminance
CE, η_L	Current efficiency
CV	Cyclic voltammetry
°C	Degree Celsius
DFT	Density functional theory
Ru-cymene	Dichloro(<i>p</i> -cymene)ruthenium (II) dimer
Bphen	4,7-Diphenyl-1,10-phenanthroline
d	Doublet
I_{DS}	Drain-source current
V_{DS}	Drain-source voltage
V_D	Drain voltage

LIST OF ABBREVIATIONS (CONTINUED)

ABBREVIATION	FULL WORD
EL	Electroluminescence
ETL	Electron transport layer
eV	Electron volt
EML	Emission layer
E _g	Energy gap
E _{HOMO}	Energy level of HOMO
E _{LUMO}	Energy level of LUMO
eq.	Equivalent
FT-IR	Fourier-transform infrared spectroscopy
F	Farad
V _{GS}	Gate-source voltage
V _G	Gate voltage
GC	Glassy carbon electrode
g	Gram
E _{1/2, Fe/Fe+}	Half potential of ferrocene/ferrocenium redox couple
T _{sub}	Heat substrate
Hz	Hertz
HMBC	Heteronuclear multiple bond correlation spectroscopy
HOMO	Highest occupied molecular orbital
HTL	Hole transport layer
hr	Hour
ITO	Indium tin oxide
IC	Internal conversion
ISC	Intersystem crossing
τ	Lifetime
LCDs	Liquid crystal displays
LUMO	Lowest unoccupied molecular orbital

LIST OF ABBREVIATIONS (CONTINUED)

ABBREVIATION	FULL WORD
Lm	Lumen
<i>L</i>	Luminance
m/z	Mass/charge ratio
MS	Mass spectroscopy
$\lambda_{\text{max, abs}}$	Maximum absorption wavelength
$\lambda_{\text{max, em}}$	Maximum emission wavelength
λ_{max}	Maximum wavelength
M	Mega
m.p.	Melting point
MADN	2-Methyl-9,10-bis(naphthalen-2-yl)anthracene
μA	Microampere
μm	Micrometer
μmol	Micromole
mbar	Millibar
mg	Milligram
mL	Milliliter
mm	Millimeter
mmol	Millimole
mV	Millivolt
min	Minute
μ	Mobility
M	Molarity
m	Multiplet
nm	Nanometer
ns	Nanosecond
NPB	(<i>N,N'</i> -diphenyl)- <i>N,N'</i> -bis(<i>1</i> -naphthyl)- <i>1,1'</i> -biphenyl- 4,4'-diamine

LIST OF ABBREVIATIONS (CONTINUED)

ABBREVIATION	FULL WORD
NMR	Nuclear magnetic resonance spectroscopy
OTS	Octadecyltrichlorosilane
I_{on}/I_{off}	On/off current ratio
λ_{onset}	Onset of absorption spectra
$E_{ox, onset}$	Onset of oxidation potential
$E_{re, onset}$	Onset of reduction potential
OFETs	Organic field effect transistors
OLEDs	Organic light emitting diodes
ppm	Part per million
%	Percentage
PL	Photoluminescence
π	Pi
PE, η_P	Power efficiency
$^1\text{H NMR}$	Proton nuclear magnetic resonance spectroscopy
QY	Quantum yield
s	Second
σ	Sigma
Si/SiO ₂	Silicon wafer
s	Singlet
S	Singlet state
V_S	Source voltage
cm ²	Square centimeter (unit of surface)
m ²	Square meter (unit of surface)
TMS	Tetramethylsilane
TGA	Thermogravimetric analysis
TLC	Thin layer chromatography
V_T	Threshold voltage

LIST OF ABBREVIATIONS (CONTINUED)

ABBREVIATION	FULL WORD
t	Triplet
T	Triplet state
$V_{\text{turn on}}$	Turn-on voltage
2D NMR	Two-dimensional nuclear magnetic resonance spectroscopy
UV	Ultraviolet
V	Volt
% v/v	Volume/volume percent concentration
cm^{-1}	Wavenumber