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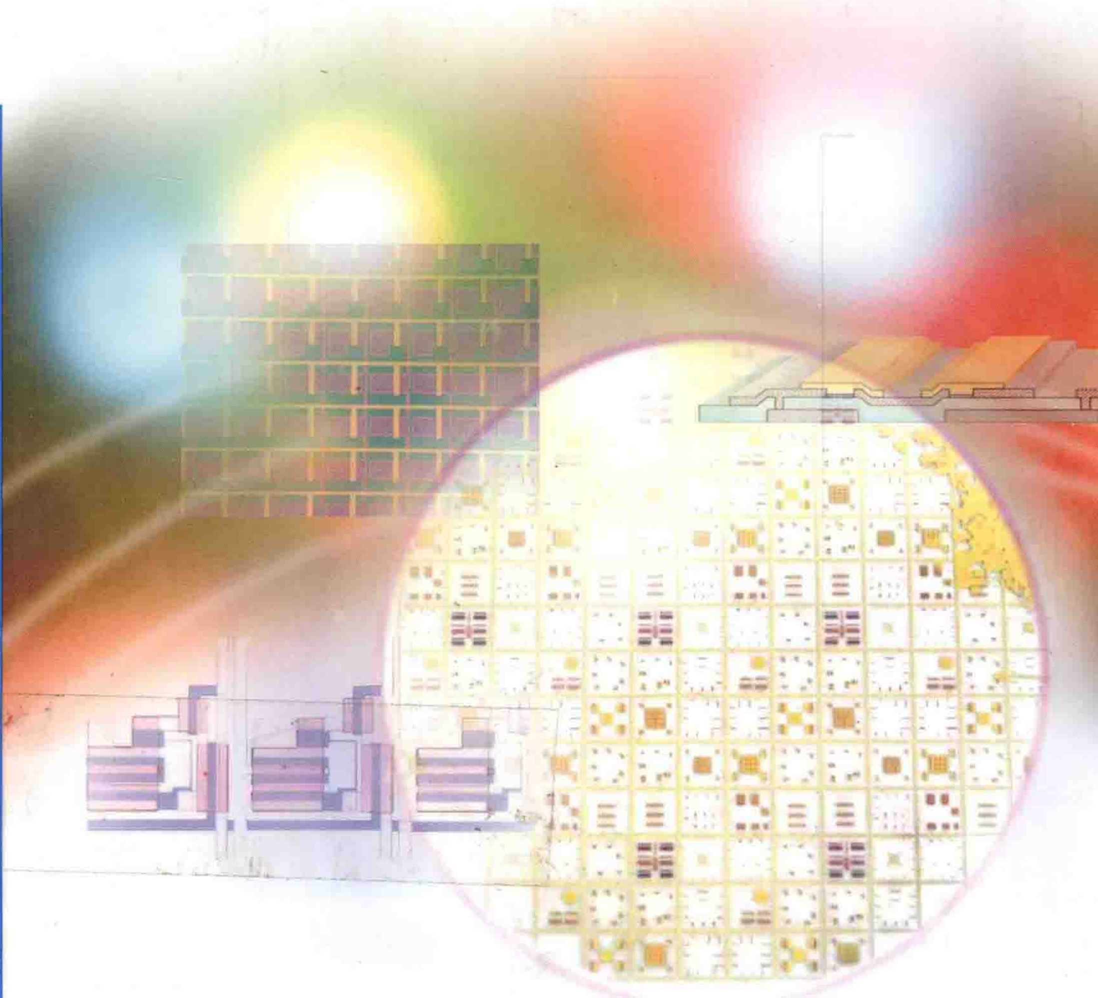
A Hybrid Approach



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Organic Thin Film Transistor Integration

Flora M. Li is currently a Senior Scientist at Polymer Vision, Eindhoven, The Netherlands. Prior to this, she was a Research Associate/NSERC Postdoctoral Fellow at the Centre of Advanced Photonics and Electronics (CAPE) in the Electrical Engineering Division of the University of Cambridge, UK. She received her Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Canada, in 2008. She was a Visiting Scientist at Xerox Research Centre of Canada (XRCC) from 2005–2008. Her research interests are in the field of nano- and thin-film technology for applications in large area and flexible electronics, including displays, sensors, photovoltaics, circuits and systems. Dr. Li has co-authored a book entitled CCD Image Sensors in Deep-Ultraviolet (2005), and has published articles in various scientific journals.

Arokia Nathan holds the Sumitomo/STS Chair of Nanotechnology at the London Centre for Nanotechnology, University College, London, and is a recipient of the Royal Society Wolfson Research Merit Award. He is also the CTO of Ignis Innovation Inc., Waterloo, Canada, a company he founded to commercialize technology on thin film silicon backplanes on rigid and flexible substrates for large area electronics. He has held Visiting Professor appointments at the Physical Electronics Laboratory, ETH Zürich and at the Engineering Department, University of Cambridge, UK. He received his Ph.D. in Electrical Engineering from the University of Alberta. He held the DALSA/NSERC Industrial Research Chair in sensor technology, was a recipient of the 2001 Natural Sciences and Engineering Research Council E.W.R. Steacie Fellowship, and was awarded the Canada Research Chair in nano-scale flexible circuits. Professor Nathan has published extensively in the field of sensor technology and CAD, and thin film transistor electronics, and has over 40 patents filed/awarded. He is the co-author of two books, Microtransducer CAD and CCD Image Sensors in Deep-Ultraviolet, and serves on technical committees and editorial boards in various capacities.

Yiliang Wu received his Ph.D. degree in polymer science from the Tokyo Institute of Technology, Japan, in 1999. After two years of postdoctoral studies at Queen's University, Kingston, Canada, he joined the Xerox Research Centre of Canada in 2001 as a research scientist working on organic transistor materials design and process. Currently, Dr. Wu is a Principal Scientist at the centre, leading Xerox's Printable Electronic Materials project. He is the holder of over 85 US patents and has authored/co-authored 78 peer-reviewed papers and two book chapters.

Beng Ong is Program Director of Polymer & Molecular Electronics and Devices for the Science & Engineering Research Council (SERC), Agency for Science, Technology and Research (A*Star), and Director at the Institute of Materials Research & Engineering (IMRE), Singapore. He currently also holds positions as a Professor at the Nanyang Technological University, Singapore, as Adjunct Professor at McMaster University and the University of Waterloo, Canada, as Fellow/Visiting Professor at Shanghai JiaoTong University and as an Honorary Professor at the East China University of Science and Technology in Shanghai. Prior to his relocation to Singapore in 2007, Professor Ong was a Senior Fellow of the Xerox Corporation, and a manager of Advanced Materials and Printed Electronics at the Xerox Research Centre of Canada. Professor Ong currently has a patent portfolio of 187 US patents and about 100 refereed papers on enabling materials, processes, and integration technologies. Many of the technology programs he managed at Xerox have won awards including the Nano-50 Award for Materials Innovation (2007) and for Nanotechnology Commercialization (2007), the ACS Innovation Award (2006), the Connecticut Quality Improvement Gold Award (2006), and the Wall Street Journal Technology Innovation Runner-up Award (2005).

Flora Li dedicates this book to her extraordinarily amazing family, for their unconditional love and unwavering support: David, Adda, Christina, Ben, and 婆婆

Preface

Organic semiconductors offer great promise for large area, low-end, lightweight, and flexible electronics applications. Their technological edge lies not only in their ease of processability but in their ability to flex mechanically. This makes them highly favorable for implementation on robust substrates with non-conventional form factor. Since its proof of concept in the early 1980s, progress in organic electronics has been impressive with performance attributes that are competitive with the inorganic counterparts. In particular, organic electronics is attractive from the standpoint of complementing conventional silicon technology, thriving in a different market domain that targets lower resolution, cost-effective mass production items such as identification tags, smart cards, smart labels, and pixel drivers for display and sensor technology.

While the material properties and processing technology for organic semiconductors continue to advance and mature, progress in organic thin film transistor (OTFT) integration and its scalability to large areas has not enjoyed the same pace. A major driving force behind this technology lies in the ability to manufacture low-end, and disposable electronic devices. This in turn demands a fabrication process that allows high volume production at low cost. The process should be able to produce stand-alone devices, device arrays, and integrated circuits of acceptable operating speed, functionality, reliability, and lifetime. However, this comes with its fair share of challenges, which we have attempted to address in this book. It is intended as a text and/or reference for graduate students in Electrical Engineering, Materials Science, Chemistry, and Physics, and engineers in the electronics industry.

Most of the results presented here stem from research conducted at the Giga-to-Nano Labs, University of Waterloo, and the Xerox Research Centre of Canada (XRCC), which granted access to its high quality, high performance, stable organic semiconductor materials. We acknowledge the contributions of several colleagues in these laboratories whose expertise ranged from materials processing and TFT integration to circuit and system design. We especially thank Prof. A. Sazonov (University of Waterloo), Dr Yuri Vygranenko (Instituto Superior de Engenharia de Lisboa), Dr D. Striakhilev (Ignis Innovation Inc.), Prof. P. Servati (University of British Columbia), Dr S. Koul (General Electric), Dr M.R.E. Rad (T-Ray Science), Dr C.-H. Lee (Samsung Electronics), Dr G. Chaji (Ignis Innovation Inc.),

Dr K. Sakariya (Apple Computers), Dr S. Sambandan (PARC), Dr H.-J. Lee (DALSA Inc.), Dr K. Wong (University of Waterloo), R. Barber (University of Waterloo), Dr G.-Y. Moon (LG Chemicals), Dr I.W. Chan (ETRI).

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The text has evolved from a series of courses offered to graduate students in Electrical Engineering as well as doctoral dissertations covering different aspects of large area electronics. The scope of this book is to advance OTFT integration from an engineering perspective, and not material development, which is the strength of chemical physicists. By assimilating existing materials, techniques and resources, the book explores a number of approaches to deliver higher performance devices and demonstrate the feasibility of organic circuits for practical applications. Much of the material in the book can be presented in about 30 hours of lecture time. The text begins with an assessment of organic electronics and market opportunities for OTFT technology. The latter is further described in Chapter 2, examining device architectures and material selection. Strategies to enable circuit integration are presented in Chapter 3, while Chapter 4 explores optimization of gate dielectric composition and structure. Interface engineering methodologies for OTFTs to enhance the dielectric/semiconductor and contact/semiconductor interfaces are described in Chapters 5 and 6. Chapter 7 presents examples of functional circuits for active-matrix display and other applications. Chapter 8 concludes with a glimpse of future challenges related to OTFT integration.

This book would not have been possible without the support of various institutions and funding agencies: University of Waterloo, Xerox Research Centre of Canada, University College London, University of Cambridge, Nanyang Technological University, Natural Sciences and Engineering Research Council of Canada, Ontario Centres of Excellence, and The Royal Society.

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Glossary

Abbreviations

AC	alternating current
AFM	atomic force microscopy
Ag	silver
Al	aluminum
Al_2O_3 or AlO_x	aluminum oxide
ALD	atomic layer deposition
AMLCD	active-matrix liquid crystal display
AMOLED	active-matrix organic light emitting diode
a-Si:H or a-Si	amorphous silicon
Au	gold
BCB	benzocyclobutene
C60	fullerene
CMOS	complementary metal oxide semiconductor
CNT	carbon nanotube
CT	charge transfer
CTC	charge transfer complex
Cu	copper
C–V	capacitance–voltage characteristics
CVD	chemical vapor deposition
D6HT	dihexyl-sexithiophene
DC	direct current
DFH-4T	diperflurorohexylquarter-thiophene
DIP	dual in-line package
DOS	density of states
Dpi	dots per inch
EDM	electro-discharge machining
E-Paper	electronic paper
ERDA	elastic recoil detection analyses
$F_{16}CuPc$	hexadecafluoro-phthalocyanine
F8T2	poly(9,9′-dioctyl-fluorene-co-bithiophene)
FTIR	fourier transform infrared spectroscopy
GIXRD	grazing-incidence X-ray diffraction

HF	hydrofluoric acid
HMDS	hexamethyldisilazane
HOMO	highest occupied molecular orbital
IC	integrated circuit
ICP	inductively coupled plasma
IEEE	Institute of Electrical and Electronics Engineers
IJP	inkjet printing
IP	ionization potential
$I-V$	current–voltage characteristics
LCD	liquid crystal display
LUMO	lowest unoccupied molecular orbital
MIS	metal-insulator-semiconductor
MOS	metal-oxide-semiconductor
MNB	2-mercapto-5-nitro-benzimidazole
Mo	molybdenum
MOSFET	metal oxide semiconductor field effect transistor
MTR	multiple trapping and release model
N_2	nitrogen
NH_3	ammonia
NMOS	n-channel or n-type metal oxide semiconductor
NW	nanowire
O_2 plasma	oxygen plasma
ODTS	octadecyltrichlorosilane
OFET	organic field effect transistor
OLED	organic light emitting diode
OTFT	organic thin film transistor
OTS or OTS-8	octyltrichlorosilane
P3HT	poly(3-hexylthiophene)
PA	polyacetylene
PANI	polyaniline
PBTTT	poly(2,5-bis(3-alkylthiophen-2-yl)thieno[3,2-*b*]thiophene)
PCBM	phenyl-C61-butyric acid methyl ester
PECVD	plasma enhanced chemical vapor deposition
PEDOT:PSS	poly(3,4-ethylene dioxythiophene) doped with polystyrene sulfonic acid
PEN	poly(ethylene naphthalate)
PET	poly(ethylene terephthalate)
Ph.D.	doctor of philosophy
PI	polyimide
PMMA	poly(methyl methacrylate)
PPV	poly(*p*-phenylene vinylene) or polyphenylene vinylene
PQT	poly(3,3‴-dialkylquaterthiophene)
Pt	platinum
PT	polythiophene
PTV	poly(thienylene vinylene)

PVA	polyvinyl acetate or polyvinyl alcohol
R&D	research and development
RCA clean	a standard set of wafer cleaning steps; RCA = Radio Corporation of America
RF	radio frequency
RFID	radio frequency identification
RIE	reactive ion etching
SAM	self-assembled monolayer
SiH_4	silane
SiN_x	silicon nitride
SiO_2	silicon dioxide
SiO_x	silicon oxide
SnO_2	tin oxide
TFT	thin film transistor
TiO_2	titanium oxide
UV	ultraviolet
UW	University of Waterloo
XPS	X-ray photoelectron spectroscopy
XRCC	Xerox Research Centre of Canada
ZnO	zinc oxide

Mathematic Symbols

φ_B	injection barrier
Φ_M	work function of the electrode (metal)
[N]/[Si]	nitrogen to silicon ratio, to describe stoichiometry or composition of SiN_x
μ_{FET}	field effect mobility
C_i	gate capacitance per unit area
C_S	storage capacitor
E_G	band-gap energy
f_{max}	maximum switching frequency
g_m	transconductance
I_D	drain current
I_G	gate current
I_{leak}	leakage current
I_{OFF}	off current
I_{ON}	on current
I_{ON}/I_{OFF}	on/off current ratio
I_S	source current
IP_S	ionization potential of the semiconductor
L	channel length
$R_{CONTACT}$	contact resistance
S	inverse subthreshold slope ($V\,dec^{-1}$)

τ	transit time
V_{BG}	bottom-gate voltage
V_{DD}	positive supply voltage
V_{DS}	drain-source voltage
V_{GS}	gate-source voltage
V_{ON}, V_{SO}	onset voltage or switch-on voltage
V_{SS}	negative supply voltage
V_T	threshold voltage
V_{TG}	top-gate voltage
W	channel width

Definitions

Definitions of selected terms cited from Wikipedia webpage. *http://en.wikipedia.org/wiki/Main_Page.*

Alkanes (also *Alkyl*)	Chemical compounds that consist only of the elements carbon (C) and hydrogen (H) (i.e., hydrocarbons), wherein these atoms are linked together exclusively by single bonds (i.e., they are saturated compounds) without any cyclic structure (i.e., loops). An alkyl group is a functional group or side-chain that, like an alkane, consists solely of singly-bonded carbon and hydrogen atoms.
Charge transfer complex (CT complex)	An electron donor–electron acceptor complex, characterized by electronic transition(s) to an excited state. In this excited state, there is a partial transfer of elementary charge from the donor to the acceptor. A CT complex composed of the tetrathiafulvalene (TTF, a donor) and tetracyanoquinodimethane (TCNQ, an acceptor) was discovered in 1973. This was the first organic conductor to show almost metallic conductance.
Conductive polymer (also *conducting polymer*)	Polymer that is made conducting, or "doped," by reacting the conjugated semiconducting polymer with an oxidizing agent, a reducing agent, or a protonic acid, resulting in highly delocalized polycations or polyanions. The conductivity of these materials can be tuned by chemical manipulation of the polymer backbone, by the nature of the dopant, by the degree of doping, and by blending with other polymers. Conductive polymer is an organic polymer semiconductor, or an organic semiconductor.

Conjugated polymer	A system of atoms covalently bonded with alternating single and double carbon–carbon (sometimes carbon–nitrogen) bonds in a molecule of an organic compound. This system results in a general delocalization of the electrons across all of the adjacent parallel aligned p-orbitals of the atoms, which increases stability and thereby lowers the overall energy of the molecule.
Dielectric (also *insulator*)	A non-conducting substance, that is, an insulator. Although "dielectric" and "insulator" are generally considered synonymous, the term "dielectric" is more often used when considering the effect of alternating electric fields on the substance while "insulator" is more often used when the material is being used to withstand a high electric field. Dielectric encompasses the broad expanse of nonmetals (including gases, liquids, and solids) considered from the standpoint of their interaction with electric, magnetic, of electromagnetic fields. In this book, the terms "dielectric" and "insulator" are used interchangeably.
Electrode (also *contact*)	An electrical conductor (e.g., metallization) used to make contact with a nonmetallic part of a circuit (e.g., a semiconductor). The gate/source/drain metal *layer* of the TFT is referred to as an electrode. The *connection* between the source/drain metal layer and the semiconductor layer (i.e., when we speak of the interface) is referred to as the "contact." In this book, the terms "electrode" and "contact" are used almost interchangeably.
Insulator (also *dielectric*)	A material that resists the flow of electric current. It is an object intended to support or separate electrical conductors without passing current through itself. An insulation material has atoms with tightly bonded valence electrons. The term electrical insulation often has the same meaning as the term dielectric.
Mobility (also *carrier mobility*, *field-effect mobility*, *effective mobility*)	The state of being in motion. *Carrier mobility* is a quantity relating the drift velocity of electrons or holes to the applied electric field across a material; this is a material property. *Field-effect mobility* or *effective mobility* describes the mobility of carriers under the influence of the device structure in field-effect transistors. Field-effect mobility is device-specific, not material-specific, and includes effects such as contact resistances, surface effects, and so on.

Organic compounds	Chemical compounds containing carbon-hydrogen (C–H) bonds of covalent character.
Organic electronics (also *plastic electronics*)	A branch of electronics that deals with conductive polymers, plastics, or small molecules. It is called "organic" electronics because the polymers and small molecules are carbon-based, like the molecules of living things. This is as opposed to traditional electronics which relies on inorganic conductors such as copper or silicon.
Organic semiconductor (also *polymer semiconductor*)	Any organic material that has semiconductor properties. Both short chain (oligomers) and long chain (polymers) organic semiconductors are known. There are two major classes of organic semiconductors, which overlap significantly: organic charge-transfer complexes, and various "linear backbone" polymers derived from polyacetylene. This book focuses on the investigation of polymer organic semiconductors; thus, in most cases, the term "organic semiconductor" and "polymer semiconductor" are used interchangeably.
OTFT (also *OFET*)	An organic thin film transistor (OTFT) or organic field effect transistor (OFET) is a field effect transistor using an organic semiconductor in its channel.
Plastic	A general term for a wide range of synthetic or semi-synthetic polymerization products. Plastics are polymers, that is, long chains of atoms bonded to one another.
Polymer	A substance composed of molecules with large molecular mass composed of repeating structural units, or monomers, connected by covalent chemical bonds.

Contents