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Organic Thin Film Transistor Integration
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Flora M. Li, Arockia Nathan, Yiliang Wu, and Beng S. Ong

Organic Thin Film Transistor Integration

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

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.

Cambridge, London, Toronto, Singapore 2010

Flora M. Li, Arokia Nathan, Yiliang Wu, and Beng S. Ong
Glossary

Abbreviations

AC  alternating current
AFM  atomic force microscopy
Ag  silver
Al  aluminum
Al$_2$O$_3$ 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  diperflurohexylquarter-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
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>HF</td>
<td>hydrofluoric acid</td>
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<tr>
<td>HMDS</td>
<td>hexamethyldisilazane</td>
</tr>
<tr>
<td>HOMO</td>
<td>highest occupied molecular orbital</td>
</tr>
<tr>
<td>IC</td>
<td>integrated circuit</td>
</tr>
<tr>
<td>ICP</td>
<td>inductively coupled plasma</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IJP</td>
<td>inkjet printing</td>
</tr>
<tr>
<td>IP</td>
<td>ionization potential</td>
</tr>
<tr>
<td>I–V</td>
<td>current–voltage characteristics</td>
</tr>
<tr>
<td>LCD</td>
<td>liquid crystal display</td>
</tr>
<tr>
<td>LUMO</td>
<td>lowest unoccupied molecular orbital</td>
</tr>
<tr>
<td>MIS</td>
<td>metal-insulator-semiconductor</td>
</tr>
<tr>
<td>MOS</td>
<td>metal-oxide-semiconductor</td>
</tr>
<tr>
<td>MNB</td>
<td>2-mercapto-5-nitro-benzimidazole</td>
</tr>
<tr>
<td>Mo</td>
<td>molybdenum</td>
</tr>
<tr>
<td>MOSFET</td>
<td>metal oxide semiconductor field effect transistor</td>
</tr>
<tr>
<td>MTR</td>
<td>multiple trapping and release model</td>
</tr>
<tr>
<td>N₂</td>
<td>nitrogen</td>
</tr>
<tr>
<td>NH₃</td>
<td>ammonia</td>
</tr>
<tr>
<td>NMOS</td>
<td>n-channel or n-type metal oxide semiconductor</td>
</tr>
<tr>
<td>NW</td>
<td>nanowire</td>
</tr>
<tr>
<td>O₂ plasma</td>
<td>oxygen plasma</td>
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<tr>
<td>OTS</td>
<td>octadecyltrichlorosilane</td>
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<tr>
<td>OFET</td>
<td>organic field effect transistor</td>
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<tr>
<td>OLED</td>
<td>organic light emitting diode</td>
</tr>
<tr>
<td>OTFT</td>
<td>organic thin film transistor</td>
</tr>
<tr>
<td>OTS or OTS-8</td>
<td>octyltrichlorosilane</td>
</tr>
<tr>
<td>P3HT</td>
<td>poly(3-hexylthiophene)</td>
</tr>
<tr>
<td>PA</td>
<td>polyacetylene</td>
</tr>
<tr>
<td>PANI</td>
<td>polyaniline</td>
</tr>
<tr>
<td>PBTTT</td>
<td>poly(2,5-bis(3-alkyiithiophen-2-yl)thieno[3,2-b]thiophene)</td>
</tr>
<tr>
<td>PCBM</td>
<td>phenyl-C61-butyric acid methyl ester</td>
</tr>
<tr>
<td>PECVD</td>
<td>plasma enhanced chemical vapor deposition</td>
</tr>
<tr>
<td>PEDOT:PSS</td>
<td>poly(3,4-ethylene dioxythiophene) doped with polystyrene sulfonic acid</td>
</tr>
<tr>
<td>PEN</td>
<td>poly(ethylene naphthalate)</td>
</tr>
<tr>
<td>PET</td>
<td>poly(ethylene terephthalate)</td>
</tr>
<tr>
<td>Ph.D.</td>
<td>doctor of philosophy</td>
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<tr>
<td>PI</td>
<td>polyimide</td>
</tr>
<tr>
<td>PMMA</td>
<td>poly(methyl methacrylate)</td>
</tr>
<tr>
<td>PPV</td>
<td>poly(p-phenylene vinylene) or polyphenylene vinylene</td>
</tr>
<tr>
<td>PQT</td>
<td>poly(3,3″-dialkylquaterthiophene)</td>
</tr>
<tr>
<td>Pt</td>
<td>platinum</td>
</tr>
<tr>
<td>PT</td>
<td>polythiophene</td>
</tr>
<tr>
<td>PTV</td>
<td>poly(thienylene vinylene)</td>
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</tbody>
</table>
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
SiH4  silane
SiNx  silicon nitride
SiO2  silicon dioxide
SiOx  silicon oxide
SnO2  tin oxide
TFT  thin film transistor
TiO2  titanium oxide
UV  ultraviolet
UW  University of Waterloo
XPS  X-ray photoelectron spectroscopy
XRCC  Xerox Research Centre of Canada
ZnO  zinc oxide

Mathematic Symbols

\( \varphi_B \)  injection barrier
\( \Phi_M \)  work function of the electrode (metal)
\([N]/[Si]\)  nitrogen to silicon ratio, to describe stoichiometry or composition of SiNx
\( \mu_{FET} \)  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
\( I_{PS} \)  ionization potential of the semiconductor
\( L \)  channel length
\( R_{CONTACT} \)  contact resistance
\( S \)  inverse subthreshold slope (V dec^{-1})
\( \tau \) 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.


**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.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tr>
<td><strong>Organic compounds</strong></td>
<td>Chemical compounds containing carbon-hydrogen (C–H) bonds of covalent character.</td>
</tr>
<tr>
<td><strong>Organic electronics (also plastic electronics)</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Organic semiconductor (also polymer semiconductor)</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>OTFT (also OFET)</strong></td>
<td>An organic thin film transistor (OTFT) or organic field effect transistor (OFET) is a field effect transistor using an organic semiconductor in its channel.</td>
</tr>
<tr>
<td><strong>Plastic</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>Polymer</strong></td>
<td>A substance composed of molecules with large molecular mass composed of repeating structural units, or monomers, connected by covalent chemical bonds.</td>
</tr>
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1

Introduction

Organic semiconductor technology has attracted considerable research interest in view of its great promise for large area, low-end, lightweight, and flexible electronics applications [1]. Owing to their processability advantages and unique physical (i.e., electrical, optical, thermal, and magnetic) properties, organic semiconductors can bring exciting new opportunities for broad-impact applications requiring large-area coverage, mechanical flexibility, low-temperature processing, and low cost. Thus, organic semiconductors have appeal for a broad range of devices including transistors, diodes, sensors, solar cells, and light-emitting devices. Figure 1.1 depicts a number of application domains that can benefit from the versatility of organic electronics technology [2]. Since their proof of concept in the 1980s, the impressive development in organic semiconductor materials has led to performance properties that are competitive with amorphous silicon (a-Si), increasing their suitability for commercial applications [3].

The transistor is a fundamental building block for all modern electronics; transistors based on organic semiconductors as the active layer are referred to as organic thin film transistors (OTFTs). A number of commercial opportunities have been identified for OTFTs, including flat panel active-matrix liquid crystal displays (LCDs) or active matrix organic light-emitting diode displays (AMOLEDs), electronic paper (e-paper), low-end data storage such as smart cards, radio-frequency identification (RFID) and tracking devices, low-cost disposable electronic products, and sensor arrays; more applications continue to evolve as the technology matures [4]. Figure 1.2 illustrates a few commercial opportunities envisioned for OTFTs.

The unique features which give organic electronics a technological edge are simpler fabrication methods and the ability to mechanically flex. Fabrication of organic electronics can be done using relatively simple processes such as evaporation, spin-coating, and printing, which do not require high-end clean room laboratories. For example, solution-processable organic thin films can be deposited by spin coating, enabling fast and inexpensive coverage over large areas. Inkjet printing techniques can be used to deposit soluble organic inks. In addition, low-temperature processing and the mechanical flexibility of organic materials make them highly favorable for implementation on robust substrates.
with non-conventional form factors. In general, organic electronic devices are not expected to compete with silicon devices in high-end products, because of their lower speed as compared to silicon. Thus organic electronics is intended to complement conventional silicon technology. It is expected to thrive in a different market domain targeting lower resolution, cost-effective mass production items such as identification tags, smart cards, and pixel drivers for display and sensor technology.
1.1 Organic Electronics: History and Market Opportunities

Historically, organic materials (or plastics) were viewed as insulators, with applications commonly seen in inactive packaging, coating, containers, moldings, and so on. Research on the electrical behavior of organic materials commenced in the 1960s [5]. Photoconductive organic materials were discovered in the 1970s and were used in xerographic sensors. The announcement of conductive polymers in the late 1970s [6], and of conjugated semiconductors and photoemission polymers in the 1980s [7], gave new impulse to the activity in the field of organic electronics. Polyacetylene was one of the first polymers reported to be capable of conducting electricity [8], and it was discovered that oxidative doping with iodine causes the conductivity to increase by 12 orders of magnitude [9]. This discovery and the development of highly-conductive organic polymers was credited to Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, who were jointly awarded the Nobel Prize in Chemistry in 2000 for their 1977 discovery and development of oxidized, iodine-doped polyacetylene.

The continued evolution of organic semiconductor materials from the standpoint of electrical stability, processability, functionality, and performance is enabling realization of high-performance devices in laboratory environments [10–14]. The advancement in organic semiconductor materials is starting to prompt the transition of the technology from an academic research environment to industrial research and development (R&D). The shift toward industrial R&D is aided by the establishment of several government-sponsored research initiatives [15, 16], the founding of various organic electronics driven associations and companies [17–19], and the development of IEEE standards for the testing of organic electronics devices [20]. The increased cooperative efforts between academia, industry, and government are vital to the development of a strong materials and manufacturing infrastructure [21–26].

The outlook for low-cost production of organic electronics is a key driver for market opportunities in this area. To achieve these cost targets, low-cost materials, cost-effective processes, and high-volume manufacturing infrastructure are required. The development of high-volume roll-to-roll manufacturing platforms for fabrication of organic circuits on continuous, flexible, low-cost substrates, has been reported. These platforms are based on the integration of lithography, vacuum deposition, and printing technologies. It has been forecast that an organic semiconductor fabrication facility can be built for far less than the cost of a silicon semiconductor fabrication facility [3]. The high cost of silicon-based foundries can be attributed to the sophisticated wafer processing and handling equipment, high-resolution lithography tools, wafer testing equipment, clean-room environment, and costly chemical distribution and disposal facilities. In contrast, the cost reduction forecast for an organic electronic manufacturing facility is expected to be derived from lower materials cost, less sophisticated equipment, simpler manufacturing technologies, less stringent demands on clean-room settings, and reduced
waste output. However, the potential savings in the manufacturing cost of organic electronics come with the trade-off of lower performance.

Figure 1.3 provides a conceptual view of the cost-and-performance sectors served by silicon technology and organic semiconductor technology. It must be noted that organic semiconductor devices do not offer the same electrical performance as silicon devices. While silicon technology is aimed for high-end, high performance, and high processing power electronic products, organic semiconductor technology appeals for lower-end, cost-effective disposable electronics products.

One of the most frequently discussed opportunities for organic electronics is their integration as the driver backplane of flexible displays. Specifically, printed organic semiconductor materials are strong candidates for novel electrically active display media. The same applies to radio frequency interrogation devices. An overview of these OTFT-based applications and their current market status is presented next. Note that, at present, a-Si thin film transistors (TFTs) and polycrystalline silicon (poly-Si) TFTs are the key backplane technologies used in flat panel display products. Therefore, OTFTs are not intended to displace a-Si TFTs in large-area high-resolution flat panel displays. Instead, they will have a bigger impact on lower-cost flexible displays and e-paper applications. The key features of OTFT and a-Si TFT are compared in Table 1.1.

1.1.1 Large-Area Displays

The application of OTFTs for large area displays has been demonstrated by a number of companies and research institutions. For example, Plastic Logic Ltd. demonstrated the integration of an OTFT-driven backplane to a Gyricon display in 2003 [27]. The active-matrix display backplane was inkjet printed and drove a 3000-pixel display that was fabricated on glass. In early 2007, the world’s first factory was built to produce plastic electronic devices [18].

A number of corporations have also invested in R&D for OTFT-driven large area displays. Examples include Sony, Samsung, Kodak, LG Philips, Motorola, 3M, and
Table 1.1  Comparison of OTFTs and amorphous silicon (a-Si) TFTs.

<table>
<thead>
<tr>
<th></th>
<th>OTFT</th>
<th>a-Si TFT</th>
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<tbody>
<tr>
<td>Material</td>
<td>Organic semiconductor as active layer; p-type, n-type, ambipolar</td>
<td>a-Si as active layer</td>
</tr>
<tr>
<td>Processing</td>
<td>Spin-coat, print, evaporation. Low temperature (e.g., room temperature)</td>
<td>Plasma enhanced chemical vapor deposition (PECVD)</td>
</tr>
<tr>
<td>Mobility</td>
<td>Can be comparable to a-Si</td>
<td>~1 cm² V⁻¹ s⁻¹</td>
</tr>
<tr>
<td>Substrate and form</td>
<td>Variety of substrates and flexible form factor</td>
<td>Glass (most common), Plastic (in development)</td>
</tr>
<tr>
<td>Mechanical flexibility</td>
<td>Bendable</td>
<td>Fragile and brittle</td>
</tr>
<tr>
<td>Electrical stability</td>
<td>Rapid degradation, but degradation stabilizes (may be favorable for devices that turn on for a longer time)</td>
<td>Slower bias-induced degradation, but degradation does not stabilize</td>
</tr>
<tr>
<td>Pros</td>
<td>Potentially no clean-room, lower cost</td>
<td>More mature and stable</td>
</tr>
<tr>
<td>Cons</td>
<td>Process challenge; device performance, stability, and lifetime</td>
<td>Mechanical flexibility (stress), Higher processing temperature</td>
</tr>
<tr>
<td>Key applications</td>
<td>Numerous: displays, RFID tags, sensors, disposable electronics</td>
<td>Circuits for large-area displays and sensors array backplane</td>
</tr>
<tr>
<td>Outlook</td>
<td>New opportunities: smaller/flexible displays, disposable electronics, smart textiles</td>
<td>Continue to excel in AMLCD, AMOLED, active-matrix sensor technologies</td>
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Hewlett-Packard. In 2007, Sony demonstrated a 2.5 in. AMOLED display driven by OTFTs [28]; LG Philips’ LCD Division presented a high resolution active-matrix liquid crystal display (AMLCD) with an OTFT-driven backplane fabricated using solution processing [29]; and Samsung Electronics reported an active-matrix display using printed OTFTs [30].

1.1.2  Rollable Displays

The mechanical flexibility of organic materials makes them particularly attractive for rollable or flexible displays. Polymer Vision, a spin off from Royal Philips Electronics, was a pioneer in demonstrating the capability of rollable displays, which were produced by combining ultrathin flexible OTFT-driven active-matrix backplane technology and flexible electronic ink (E-Ink) display technology. In January 2008, Polymer Vision introduced their first rollable display product,
called Readius®, a pocket-sized device, combining a 5” rollable display with high speed connectivity. The Readius® demonstrated a merger of the reading-friendly strengths of electronic-readers with the high mobility features of mobile phones, along with instant access to personalized news and information [31]. Demand for larger mobile displays is accelerating as telecom players push mobile content and mobile advertisements. The solution is to unroll the display when needed and simply store it away when not in use. Therefore, rollable display enabled devices are expected to be an emerging commodity for new generations of portable communication devices, thus presenting exciting commercial opportunities for OTFT-driven display backplane technology.

1.1.3 Radio Frequency Identification (RFID) Tag

One of the frequently promoted applications for organic electronics is the RFID tag. The RFID tag is a wireless form of automated identification technology that allows non-contact reading of data, making it effective for manufacturing, inventory, and transport environments where bar code labels are inadequate. Advantages of organic-based RFID tags over silicon-based tags include mechanical flexibility (e.g., bendable) and direct fabrication onto large area substrates using simple printable methods. The attractiveness of printed organic semiconductor materials and manufacturing platforms has drawn the involvement of several companies (e.g., 3M, Siemens), start-ups (e.g., OrganicID, ORFID Corp.), and research institutions to develop technology for organic-based RFID tags [25, 26]. For example, a 64-bit inductively-coupled passive RFID tag on a plastic substrate was demonstrated, operating at 13.56 MHz and with a read distance of over 10 cm. These specifications are approaching item-level tagging requirements, paving the way for low-cost high-volume production of RFID tags, with the potential to replace barcodes [19, 32, 33].

1.1.4 Technological Challenges

Organic electronics have reached early stages of commercial viability. Personal electronic devices incorporating small displays based on organic light-emitting diodes (OLEDs) are now available. However, many challenges still remain that are currently hindering the wide adoption of OTFTs in electronic devices. The shortcomings of OTFTs include limited charge carrier mobilities, high contact resistance, relatively higher operating voltages, device reliability issues (e.g., stability, shelf-life under operation), and limited availability of robust/mature patterning techniques and fabrication processes that are compatible with organic thin films. These technical challenges can be grouped into two categories: device performance and device manufacture.