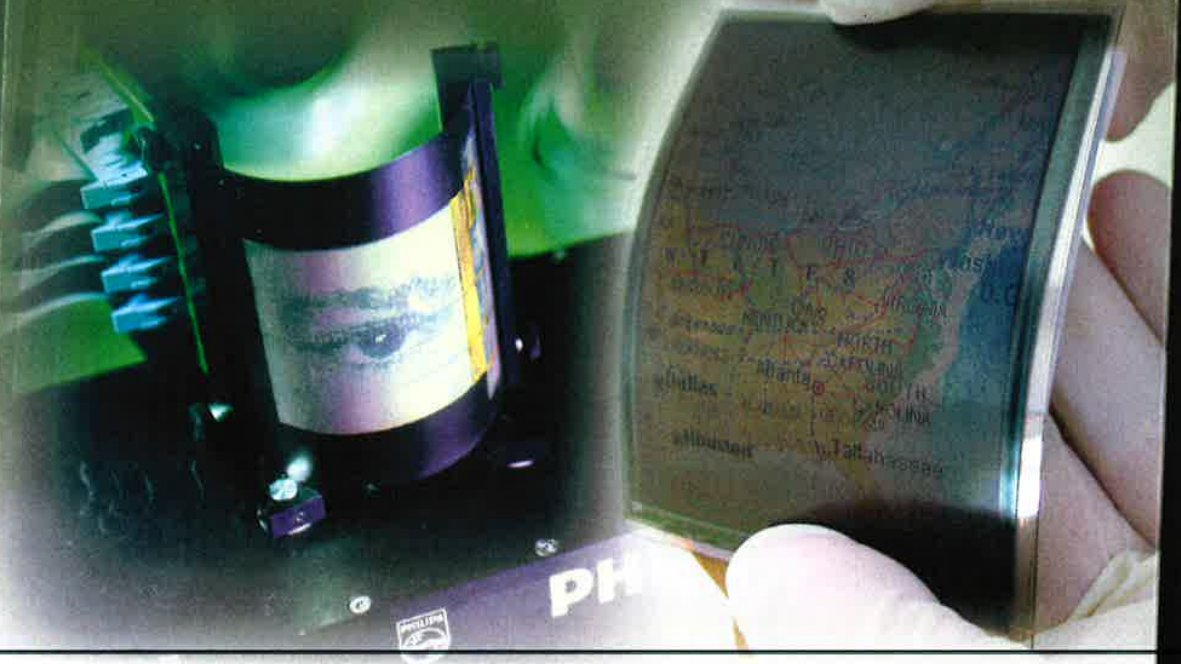
flexible flat panel displays

Editor **Gregory P. Crawford**



WILEY SID Series in **Display Technology**

Reprinted with corrections September 2005

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Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

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John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

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Library of Congress Cataloging-in-Publication Data

Flexible flat panel displays / edited by Gregory P. Crawford.
p. cm.
Includes bibliographical references and index.
ISBN-13 978-0-470-87048-8 (alk.paper)
ISBN-10 0-470-87048-6 (alk. paper)
1. Information display systems. 2. Liquid crystal displays.
3. Electroluminescent display systems.
I. Crawford, Gregory Philip.
TK7882.I6F54 2005
621.3815'422–dc22 2005003238

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-13 978-0-470-87048-8 (HB)
ISBN-10 0-470-87048-6 (HB)

Typeset in 10/12pt Times by Thomson Press (India) Limited, New Delhi
Printed and bound in Great Britain by Antony Rowe Ltd., Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

15

OLED Displays on Plastic

Mark L. Hildner

DuPont Displays

15.1 Introduction

Organic light-emitting diode (OLED) technology has captured tremendous interest and has rapidly developed since the discovery of organic electroluminescence roughly 15 years ago. Commercial OLED displays on glass are now available and the industry is poised for substantial growth in the next few years. Much of the attention given to OLEDs is due to the performance advantages that it has over other types of flat panel display (FPD) technologies, including the industry dominant liquid crystal displays (LCDs). Recognized advantages include nearly Lambertian emission, which provides wider viewing angles than LCD; fast response times, which facilitate grayscale and video capabilities in active matrix applications; and low-voltage operation, which leads to low-cost components and low-profile packaging. Furthermore, the high efficiency of OLED materials makes OLED the lowest-power emissive FPD technology and offers the potential for lower power consumption than backlit LCDs.

An additional factor giving OLED technology impetus, perhaps to an extent equal to the performance advantages, is the perception that OLEDs are a natural choice for flexible displays. The very thin structure (the active layers are less than 1 μm), solid-state construction (there is no cell gap as in an LCD), and active material composition of an OLED are very suitable for flexibility. These characteristics, combined with the performance characteristics, have many thinking that OLED is the technology path to high-performance full-color flexible displays.

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The two main types of OLED are based on small molecules and conjugated polymers. Small-molecule OLEDs (SMOLEDs) were first reported by Tang and VanSlyke (1987) and are typically thermally evaporated. Light emission from polymer OLEDs (PLEDs) was first reported by Burroughes *et al.* (1990), where a solution-processable precursor polymer was deposited by spin coating and then thermally converted at high temperature ($\geq 250\,^{\circ}C$). Then Braun and Heeger (1991) were able to make a light-emitting device with a polymer that was soluble in its conjugated form, thus eliminating the need for high-temperature processing. Solution processing at low temperatures may revolutionize how displays are manufactured because it permits a number of process options (spin coating, inkjet printing, dipping, spraying, etc.) that are lower cost than vacuum deposition; it would replace much of the vacuum processing used in today's FPD fab; it can cover large areas; and it is well suited for roll-to-roll manufacturing, which may lead to further cost reduction from the current batch process. That is why this chapter will focus on conjugated polymer OLEDs.

A number of flexible materials are being explored as OLED substrates. The first flexible OLED display demonstration was on a transparent plastic substrate (Gustafsson *et al.* 1992). Plastic is a logical choice because its transparency allows much of the architecture of an OLED on glass to be used. Plastic is rugged, more so than regular glass; able to be accurately cut with a laser, allowing for irregular shapes with the only downside being some discoloration at the cutting site; and is already incorporated into roll-to-roll process technology, both in its own manufacture and current applications.

While flexibility may be the ultimate goal for OLED displays on plastic, there are significant opportunities that are less technologically demanding than a display that can be flexed or rolled up multiple times. A flat plastic OLED display is thin, lightweight, and rugged. These are significant attributes that may be taken advantage of in mobile applications. Plastic displays can be easily cut into a wide variety of nonrectangular shapes, and can be bent into a curved, but rigid, format. These characteristics allow greater freedom in product design. Even for these nonflexible display manifestations, there are significant development challenges to bringing a plastic OLED display to the marketplace.

After a brief introduction describing how a PLED display works, this chapter will present the challenges associated with two key technology developments that must take place. The first is to obtain a plastic substrate that can withstand processing and lead to a reliable and long-lived device. The second is to obtain an understanding of the manufacturing issues associated with a plastic substrate, and then to incorporate this understanding into device processing. The issues associated with making a passive matrix (PM) OLED will then be discussed, and finally, there will be a review of thin film transistor technologies that are appropriate for plastic active matrix (AM) backplanes.

15.2 PLED Basics

15.2.1 Conjugated Polymers

Conjugated polymers are characterized by alternating single and double or single and triple bonds (Heeger 2001). Overlapping of the p_z orbitals from the double or triple bonds along the polymer backbone leads to the formation of a delocalized π-bonding system. This gives rise to energy bands similar to those in an inorganic semiconductor. The occupied π-band, analogous to the valence band, is comprised of hole-transport states, and the highest

occupied molecular orbital (HOMO) is analogous to the valence band edge. The unoccupied π^*-band, analogous to the conduction band, is comprised of electron-transport states, and the lowest unoccupied molecular orbital (LUMO) is analogous to the conduction band edge. Despite this analogy, charge transport in conjugated polymers differs in a number of ways from that in inorganic semiconductors (Patel *et al.* 2002): intrinsic and extrinsic carriers are generally negligible and conduction is dominated by injected carriers; the polymer chains distort around the charge carrier so that the charged excitation is best described as a polaron (the charge plus the distortion); and the energy bands are inhomogeneously broadened due to the amorphous polymer structure and, therefore, transport is through hopping along or between polymer chains.

15.2.2 Light-Emitting Diodes

A conjugated polymer can emit light because it has an energy gap. Figure 15.1 shows three common light-emitting polymers: poly(*p*-phenylenevinylene) or PPV; poly[2-methoxy,

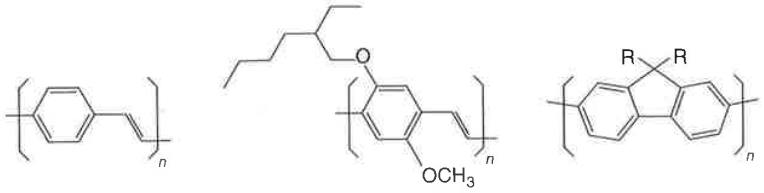

Figure 15.1 Example light-emitting conjugated polymers

5-(2′-ethyl-hexyloxy)-*p*-phenylenevinylene] or MEH-PPV; and polyfluorine. The basic polymer light-emitting device (a diode) consists of a light-emitting polymer (LEP) film of ~100 nm sandwiched between an optically transparent anode, which sits on an optical quality glass or plastic substrate, and a metallic cathode. The anode is usually indium tin oxide (ITO), which has a high work function, whereas the cathode is typically a low work function metal such as Ca or Mg. When a bias greater than the difference between the anode and cathode work functions (the built-in potential) is applied as illustrated in the band diagram of Figure 15.2(a), electrons are injected from the cathode into the π^*-band, and holes are injected from the anode into the π-band. The injected charges (electron and hole type polarons) form bound polaron-excitons, i.e. neutral bipolarons bound by their Coulomb attraction and their shared distortion (Heeger 2001). Electroluminescence (EL) results from the radiative decay (electron–hole recombination) of these excitons. The device is a diode because application of a reverse bias prevents charge flow (there is no light emission). The energy gap and thus the emission color of the diode can be tuned by changing the length of the polymer molecule, by changing the structure of the polymer repeat unit, by making copolymers, and/or by making polymer blends (Braun *et al.* 1992; Berggren *et al.* 1994; Akcelrud 2003).

A number of factors influence the efficiency of this EL process (Patel *et al.* 2002). Barriers to injection result from the mismatches of the anode and cathode work functions with the HOMO and LUMO, respectively; this defines the need for a high work function anode and a

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