

Second Edition

Flexible Flat Panel Displays

EDITED BY

DARRAN R. CAIRNS • DIRK J. BROER • GREGORY P. CRAWFORD



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Series Editor's Foreword

The first edition of Professor Crawford's *Flexible Flat Panel Displays* was one of the first volumes in the Wiley-SID series of technical books to be published. Since its appearance it has achieved the distinction of becoming the single most successful work in the series, based on cumulative sales. These facts illustrate the continuing importance and the technical challenge of mass producing high-quality, reliable devices in a flexible format, as well as the comprehensive analysis of the technical issues involved, which the editor and authors brought to the topic. In 2005 when the first edition was produced, the whole field of flexible displays was immature, and the volume necessarily focused mainly on the enabling technologies and technical challenges faced by those seeking to develop flexible devices and routes to their mass manufacture.

Today, the status of these devices has been transformed, and this new and completely revised edition of the book reflects that. Foldable organic light-emitting diode (OLED) displays are widely available on mobile phones and tablet devices, albeit restricted mainly to premium devices, while flexible liquid-crystal displays (LCDs) and especially electrophoretic displays have achieved maturity. The potential of large-area conformable displays to open new fields of application and product design is rapidly expanding in areas such as automotive interiors and industrial systems, while curved computer monitors are firmly established as mainstream devices. Meanwhile, the aspiration of product engineers to exploit displays with the free flexibility of paper or fabric remains problematic. The technical challenges which flexible devices face are in many cases the same as those that could be addressed in the first edition; bending any electronic device can lead to undesirable consequences ranging from a reversible shift in semiconductor characteristics through fatigue failure of different materials to catastrophic failure of conductor tracks, encapsulation, or the thin-film transistors (TFTs) themselves. However, state-of-the-art solutions to these difficulties have in many cases advanced both in technical approach and in performance in ways which could hardly be dreamed of in 2005. Encapsulation materials, conductive layers, and advanced semiconductors are examples where the technology has been transformed.

In this new edition of *Flexible Flat Panel Displays* the editors Professor Cairns, Professor Crawford, and Professor Broer have assembled a comprehensive and thoroughly updated overview of the field, key challenges that remain to be overcome, and approaches to materials, processes, and operating modes to further improve the availability, quality, and durability of flexible display screens. The advances in the technology that have been achieved since the publication of the first edition have also impacted the application space for flexible devices and

forward-looking views of flexible sensor systems are also included. The work will be a valuable resource and reference, not only for scientists and engineers concerned with flexible display and electronic devices but for all interested in current developments in display technology, in integrating displays in new products, and in such diverse areas as Internet of Things and wearable devices.

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Introduction

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1.1 Toward Flexible Mobile Devices

Displays and how we use them have gone through some major changes already in the twenty-first century. Mobile displays have developed from displaying text and some rudimentary graphics to highly interactive, high-resolution devices capable of streaming high-definition video. In addition to the advances in the display technologies, mobile devices also have high-resolution cameras, multiple internal sensors, powerful computer processors, multiple communication chips, and large area rechargeable batteries. Against this backdrop the requirements for flexible displays to be used in many mobile device applications far exceed those near the turn of the century. However, despite these challenging requirements, there are now beginning to be commercial products with amazing capabilities. An example of the type of approach that can be used to develop commercial foldable displays is described by Meng-Ting Lee et al. in Chapter 9. The significant improvements in organic light-emitting diodes (OLEDs) have opened possibilities in the development of foldable displays.

While improvements in OLEDs have been critical to recent developments in flexible displays there are a range of other critical components that would also need to be flexible for the development of truly mobile devices. One particularly important development has been in the field of transparent conductive coatings where metallic nanowires are becoming a commercial reality with important flexible properties. This is described in detail by Jean-Pierre Simonato in Chapter 5. For some applications an outer surface of glass would be very useful as an oxygen and moisture barrier or to protect underlying layers. Some examples of flexible glass are discussed in Chapter 8 by Armin Plitchta et al. For truly flexible devices large flexible power sources such as batteries will be needed, and flexible batteries are discussed in Chapter 13 by Nicholas Winch et al.

These are certainly exciting times for the development of flexible mobile devices. We have highlighted some of the key developments we discuss in this book that could be incorporated into such a device, but we will also need to understand how flexibility impacts functionality such as the rich touch input we expect. Some important aspects of integrating touch in mobile devices is described by Darran Cairns and Anthony Weiss in Chapter 15.

1.2 Flexible Display Layers

It is likely that polymer films will be used widely in flexible displays, and this raises myriad challenges, not least of these being durability. For applications where a polymer film is part of the outermost surface of the device, cuts and abrasions of the outermost polymer layer can reduce display performance. One approach to mitigate for this is to use self-healing polymers, which is discussed by Progyateg Chakma et al. in Chapter 7. One vitally important issue is damage to inorganic layers in a flexible display which can lead to cracking this is discussed by Yves Letterier in Chapter 16.

Mechanical damage is not the only thing to be considered in flexible display components. It is also important to tune the optics of polymer for the application and to mitigate for the underlying properties of polymer substrates. This can be achieved through the design of engineered polymer films as described by Bill McDonald in Chapter 2 and through the design of optical coatings as described by Owain Parri et al. in Chapter 3. The ability to tune properties in multiple ways opens a range of ways to design display components.

Two additional layers that play critical roles in the development of flexible displays are optically clear adhesives, discussed by Albert Everaerts in Chapter 6, and the thin film encapsulation layer used to protect OLEDs, discussed by Robert Jan Visser and Lorenza Moro in Chapter 12. Optically clear adhesives allow components to be laminated with minimal optical losses and enable complex stacks to be engineered and assembled. We discussed earlier how OLEDs are enabling advances in flexible devices but for OLEDs to have reasonable lifetimes they must be encapsulated—and it is this encapsulation that had enabled OLEDs to become a display of choice in flexible applications. One additional component that is required for flexible devices is a flexible backplane and Zachary A. Lamport et al. describe flexible backplanes using organic transistors in Chapter 4.

1.3 Other Flexible Displays and Manufacturing

We discussed earlier how our expectations of mobile devices has changed with expectations for high-fidelity video and computing power necessitating flexible batteries and touch sensors with a high-resolution display. We have also highlighted how OLEDs have become widely used in large part because of these expectations. However, not all devices need to play high-resolution video or require significant computing power. For applications such as e-readers the requirements are very different with low-power consumption and high-contrast ratio being more important than speed. Two important technologies that have found important niches are cholesteric liquid crystal displays, described by Deng-Ke Yang in Chapter 10, and electronic paper, described by Guofu Zhou in Chapter 11. There are currently some commercial products that can be manufactured on flexible substrates even if they are not ultimately used in a flexible form factor.

For several years roll-to-roll manufacturing has been advanced as a justification for flexible electronics because of the ability to fabricate devices in volume. There are a number of challenges with roll-to-roll fabrication and some of these are highlighted by Greg Potoczny in Chapter 17. More recently robotic deposition and direct writing is opening new approaches to manufacturing allowing for precise deposition of coatings and circuitry. This manufacturing approach is discussed by Kostas Sierros and Darran Cairns in Chapter 18.

Finally, we also include two chapters related to applications. Uwadiae Obahiagbon et al. detail some applications of flexible displays in medical applications in Chapter 19. We expect this to be an exciting area moving forward. In Chapter 14, Gerwin Gelinck describes his work on large area flexible x-ray detectors, which we believe will be useful in incorporating additional sensing in flexible devices and displays.

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Engineered Films for Display Technology

W.A. MacDonald

DuPont Teijin Films

2.1 Introduction

Since the early 2000s there has been an explosion in interest in printed electronics and flexible displays in terms of both exploring the potential to develop new business opportunities and developing the technology base. The opportunity to exploit flexible substrates in roll-to-roll (R2R) production has excited the interest of the plastic films and associated processing and coating industries.

To replace a rigid substrate such as glass, however, a plastic substrate needs to be able to offer some or all of the properties of glass i.e. clarity, dimensional stability, thermal stability, barrier, solvent resistance, and low coefficient of linear thermal expansion (CLTE) coupled with a smooth surface. In addition, a further functionality such as a conductive layer might be required. No plastic film offers all these properties so any plastic-based substrate replacing glass will almost certainly be a multilayer composite structure [1–3]. However, not all applications require such a demanding property set and over the past decade plastic films have found application in areas broader than the flexible organic light-emitting diode (OLED) displays initially envisaged in the early days of the technology development. These include applications such as electrophoretic displays driven by thin-film transistor (TFT) arrays printed on plastic film, printed memory, and sensors. In addition there has been a smearing of the boundary between flexible devices and the use of printed electronics and/or flexible substrates in rigid devices – an example being the use of conductive films in touchscreens incorporated into smartphones and tablets.

This chapter will review the progress made in developing plastic substrates for flexible displays over the past decade and polyester films will be used as the main examples.

2.2 Factors Influencing Film Choice

2.2.1 Application Area

The requirements for the different applications areas envisaged for printable electronics are very different and will require substrates with different property sets.

This is summarized in Figure 2.1 and this classification is divided into “simple” organic circuitry, e.g. radio frequency identification (RFID), organic-based active-matrix backplanes,

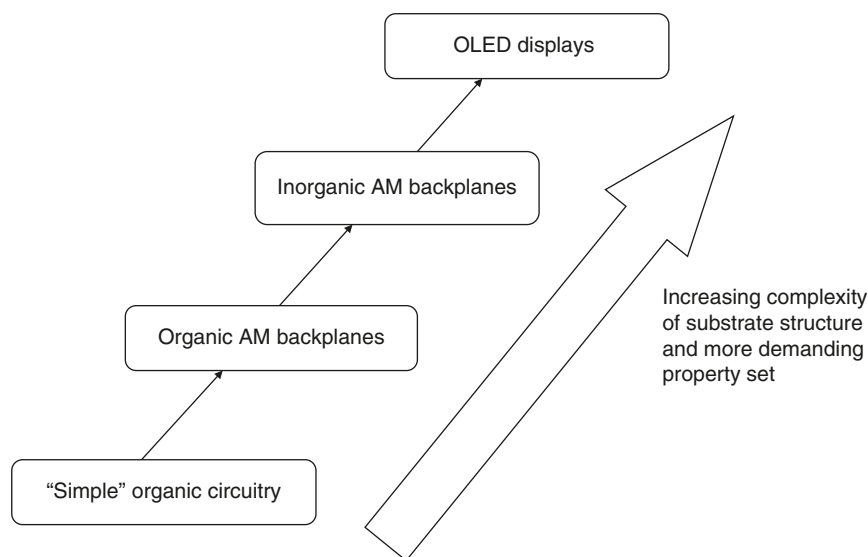


Figure 2.1 Illustration of the changing property requirements of different applications.

inorganic TFTs, and OLED displays. As one moves up the list the substrate requirements in terms of properties such as dimensional stability, surface smoothness, low coefficient of thermal stability (CLTE), conductive layers, and barrier become increasingly complex and more demanding and this will be reflected in the cost of the substrate. Substrates with low temperature stability including coated papers and oriented polypropylene film with good surface quality are adequate for some applications such as RFID and simple printed electronic devices, but a film with high temperature stability and dimensional reproducibility coupled with excellent surface quality will be required for more complex applications associated with displays such as active-matrix backplanes and OLED technology. Obviously a substrate with a property set and price commensurate with the application should be chosen and this section will focus on substrates appropriate for display application.

2.2.2 Physical Form/Manufacturing Process

The physical form of the display and whether it is

- i) flat but exploiting light weight and ruggedness,
- ii) conformable, one time fit to non-flat surface,
- iii) flexible and handleable, e.g. electronic newspaper, or
- iv) rollable

will also influence film choice. Initially in the early 2000s, the vision was of flexible OLED displays and rollable displays in particular. Over the past decade, however, with the emergence of smartphones and tablets, the general public have become used to the portability and user interface of such devices and the interest in a rollable or foldable display device has waned. At the time of writing this chapter, however, serious interest in foldable and flexible displays has again

emerged as the major electronic companies envisage flexibility as key to providing new innovation in the next generation of smartphones and tablets. In addition to this, flexible electronics offers robustness over glass-based rigid devices, and a further general trend on film substrates is to go thinner to reduce the bulkiness of a device.

Whether the film is manufactured by batch or R2R can influence film selection. Although R2R processing can be used for specific stages of device manufacture, for example barrier or conductive coatings, and for less complex printed electronic applications, for the most part more complex device manufacture such as active-matrix backplanes is carried out by a batch-based process on a rigid carrier. This fits with existing semiconductor manufacturing tooling equipment and the rigid carrier can also be exploited to control the dimensional stability. However, batch processing introduces new challenges such as bowing of the rigid carrier due to a mismatch in coefficient of thermal expansion and shrinkage behavior between the film and the rigid carrier. The major factors influencing this are the rigidity of the carrier (more rigid gives less bow) and the thickness of the film (less bow with thinner film). A second issue is release of the film from the carrier without damaging the printed circuitry and this remains an active area of research.

2.2.3 Film Property Set

2.2.3.1 Polymer Type

Polyethylene terephthalate (PET), e.g. DuPont Teijin (DTF) Films Melinex® polyester film, and polyethylene naphthalate (PEN), e.g. DuPont Teijin Films Teonex® polyester film, are biaxially oriented semicrystalline films [4, 5]. The difference in chemical structure between PET and PEN is shown in Figure 2.2.

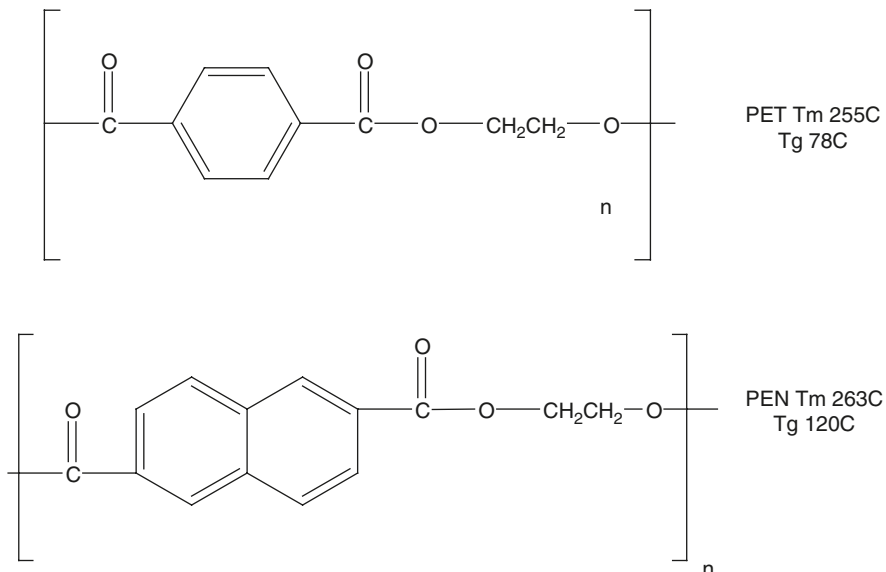


Figure 2.2 Chemical structures of PET and PEN films.

The substitution of the phenyl ring of PET by the naphthalene double ring of PEN has very little effect on the melting point (T_m), which increases by only a few degrees. There is, however, a significant effect on the glass transition temperature (T_g), the temperature at which a polymer changes from a glassy state to a rubbery state, which increases from 78°C for PET to 120 °C for PEN [2]. PET and PEN films are prepared by a process whereby the amorphous cast is drawn in both the machine direction and transverse direction. The biaxially oriented film is then heat set to crystallize the film [4, 5].

The success of polyester film in general application comes from the properties derived from the basic polymer coupled with the manufacturing process of biaxial orientation and heat setting described earlier. These properties include high mechanical strength, good resistance to a wide range of chemicals and solvents, low water absorption, excellent dielectric properties, good dimensional stability, and good thermal resistance in terms of shrinkage and degradation of the polymer chains. Fillers can be incorporated into the polymer to change the surface topography and opacity of the film. The film surface can also be altered by the use of pretreatments to give a further range of properties, including enhanced adhesion to a wide range of inks, lacquers, and adhesives. These basic properties have resulted in PET films being used in a wide range of applications, from magnetic media and photographic applications, where optical properties and excellent cleanliness are of paramount importance to electronics applications such as flexible circuitry, and touch switches, where thermal stability is key. More demanding polyester film markets, which exploit the higher performance and benefits of PEN, include magnetic media for high-density data storage and electronic circuitry for hydrolysis-resistant automotive wiring [6]. This property set provides the basis on which one can now build to meet the demands of the printed electronic market.

It is interesting to contrast these films with the other films that are currently being considered for flexible electronics applications. The main candidates are shown in Figure 2.3, which lists the substrates in terms of increasing glass transition (T_g)

The polymers can be further categorized into films that are semicrystalline (PET and PEN as mentioned earlier), amorphous and thermoplastic, and amorphous, but solvent cast. Polymers

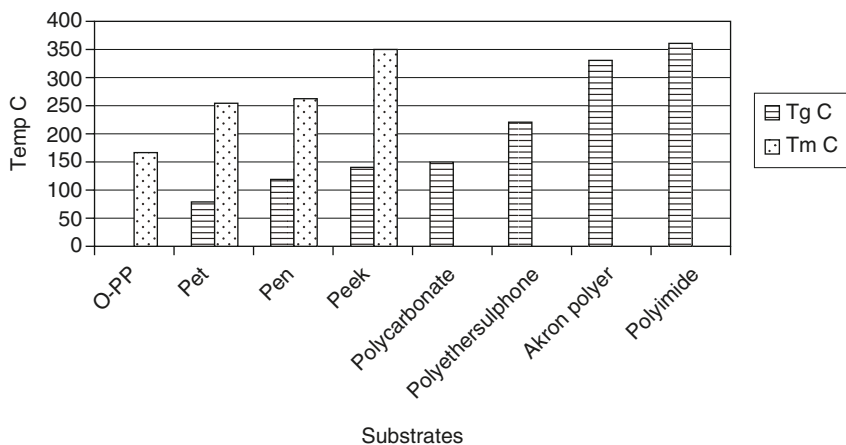


Figure 2.3 Glass transitions of film substrates of interest for flexible electronics applications.

with a T_g higher than 150°C that are semicrystalline tend generally to have a T_m that is too high to allow the polymers to be melt processed without significant degradation – Victrex® PEEKfilm ACTIV® [7] is the highest performance semicrystalline material available in film form. The next category are polymers that are thermoplastic, but non-crystalline and these range from polycarbonate (PC), e.g. Teijin's PURE-ACE® [8] and GE's Lexan® [9], with a T_g of $\sim 150^\circ\text{C}$ to polyether-sulphone (PES), e.g. Sumitomo Bakelite's Sumilite® [10], with a T_g of $\sim 220^\circ\text{C}$. Although thermoplastic, these polymers may also be solvent cast to give high optical clarity. The third category are high- T_g materials that cannot be melt processed and include substrates based on Akron Polymer Systems (APS) resins [11] and polyimide (PI), e.g. DuPont's Kapton® [12].

PET and PEN by virtue of being semicrystalline, biaxially oriented, and heat stabilized (see Section 2.3.4) have a different property set to the amorphous polymers and for simplicity these two basic categories will be used when comparing and contrasting the properties of the film types and the importance to the property set required for flexible electronic application.

2.2.3.2 Optical Clarity

The clarity of the film is important for bottom emissive displays where one is viewing through the film and a total light transmission (TLT) of $>85\%$ over 400–800 nm coupled with a haze of less than 0.7% are typical of what is required for this application. The polymers listed earlier meet this requirement apart from polyimide, which is yellow.

Polyester films are used extensively in the light management within liquid crystal displays (LCDs). PET is the base film used in brightness enhancement films (BEF) where a prismatic coating on the surface of the film is used to recycle the scattered light and direct it through the LCD to increase the brightness.

In addition to BEF and diffuser films, highly reflective polyester films are used to reflect and recycle light from the light-guide plate in an LCD display. These films are polyester films with inorganic fillers where different levels of diffuse reflectance are achieved by generating voids during the manufacturing process in Figure 2.4. These are tailored in shape, size, and distribution by controlling filler type and film process technology to achieve different levels of performance. The total reflectance spectra of these specially designed films, e.g. Melinex® RFL1 and 2, are shown in Figure 2.5 compared to a standard white film.

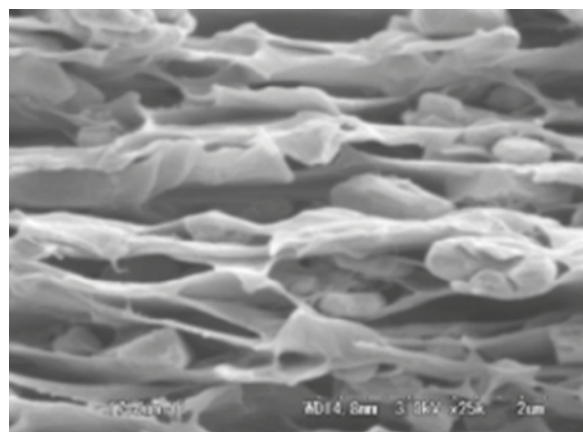


Figure 2.4 SEM of high-reflectance films illustrating the different voiding effects.