Thin Film Transistor Circuits and Systems

Reza Chaji and Arokia Nathan

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Thin Film Transistor Circuits and Systems

Providing a reliable and consolidated treatment of the principles behind large-area electronics, this book contains a comprehensive review of the design challenges associated with building circuits and systems from thin film transistors.

The authors describe the architecture, fabrication, and design considerations for the principal types of TFT, and their numerous applications. The practicalities of device non-ideality are also addressed, as are the specific design considerations necessitated by instabilities and non-uniformities in existing fabrication technologies.

Containing device-circuit information, discussion of electronic solutions that compensate for material deficiencies, and design methodologies applicable to a wide variety of organic and inorganic disordered materials, this is an essential reference for all researchers and circuit and device engineers working on large-area electronics.

Reza Chaji is the President and Chief Technology Officer at Ignis Innovation Inc., managing programs for the development of low-cost, high-yield, and low-power AMOLED displays. He is an Adjunct Professor at the University of Waterloo, Canada, and has been awarded the CMC Douglas R. Colton Medal for Research Excellence.

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"The book is an absolute must for everyone seriously interested in pixel circuits for active matrix organic light-emitting displays and flat panel imagers."

Norbert Fruehauf, University of Stuttgart

"Various TFT materials and devices have been developed for addressing liquid crystal displays and organic light-emitting diode displays. Lately, high mobility oxide semiconductors are emerging, which promises higher resolution and larger aperture ratio for improving optical efficiency. There is an urgent need for such a book to give a systematic approach to basic material properties, advanced circuit designs, and integrated operation systems for this $100B display industry. The authors are respected experts in the field. I wish to have this book on my desk soon."

Shin-Tson Wu, University of Central Florida

Preface

Advances in thin film materials and process technologies continue to fuel new areas of application in large area electronics. However, this does not come without new issues related to device-circuit stability and uniformity over large areas, placing an even greater need for new driving algorithms, biasing techniques, and fully compensated circuit architectures. Indeed, each application is unique and mandates specific circuit and system design techniques to deal with materials and process deficiencies. As this branch of electronics continues to evolve, the need for a consolidated source of design methodologies has become even more compelling. Unlike classical circuit design approaches where trends are toward transistor scaling and high integration densities, the move in large-area electronics is toward increased functionality, in which device sizes are not a serious limitation. This book is written to address these challenges and provide system-level solutions to electronically compensate for these deficiencies.

Although the circuit and system implementation examples given are based primarily on amorphous silicon technology, the design techniques and solutions described are unique, and applicable to a wide variety of disordered materials, ranging from polysilicon and metal oxides to organic families. These are complemented by real-world examples related to active-matrix organic light emitting diode displays, bio-array sensors, and flat-panel biomedical imagers. We address mixed-phase thin film and crystalline silicon electronics and, in particular, the design and interface techniques for high and low voltage circuits in the respective design spaces. The content is concise but diverse, starting with an introduction to displays, flat panel imagers, and associated backplane technologies, followed by design specifications and considerations addressing compensation and driving schemes. Here we introduce hybrid voltage-current programming, enhanced-settling current programming, and charge-based driving schemes for high-resolution pixelated architectures.

Apart from designers of imaging and display systems and the engineering community at large, this book will benefit material scientists, physicists, and chemists working on new materials for thin film transistors and sensors. It can serve as a text or reference for senior undergraduate and graduate courses in electrical engineering, physics, chemistry, or materials science. Much of the material in the book can be presented in about 30 hours of lecture time.

This book would not have been possible without the support of the Giga-to-Nano Labs at the University of Waterloo; Ignis Innovation Inc. in Waterloo; the London Centre for Nanotechnology, University College London; and the Centre for Large Area Electronics, University of Cambridge. We acknowledge the financial support provided by the Natural Sciences and Engineering Research Council, Canada, the Communications and Information Technology Ontario, Canada, and the Royal Society Wolfson Merit Award, UK.

Reza Chaji and Arokia Nathan
Waterloo and Cambridge, 2013

Contents

1 Introduction

We are witnessing a new generation of applications of thin film transistors (TFTs) for flat-panel imaging [1, 2, 3] and displays [4, 5, 6]. Unlike the active matrix liquid crystal display (AMLCD) where the TFT acts as a simple switch [7], new application areas are emerging, placing demands on the TFT to provide analog functions including managing instability arising from material disorder [3, 6].

In the following sections, we briefly describe the application platforms we have considered in this book, namely flat-panel displays and imaging, along with a summary of performance characteristics of the key TFT technologies used, or being considered, by the large-area electronics industry. While the circuit architectures reported here use examples based on amorphous silicon technology, they are easily adaptable to a broad range of materials families and applications with different specifications.

1.1 Organic light emitting diode displays

OLEDs have demonstrated promising features to provide high-resolution, potentially low-cost, and wide-viewing angle displays. More importantly, OLEDs require a small current to emit light along with a very low operating voltage (3–10 V), leading to very power efficient light emitting devices [4–6].

OLEDs are fabricated either by organic (small molecule) or polymeric (long molecule) materials. Small molecule OLEDs are produced by an evaporation technique in a high vacuum environment [8],

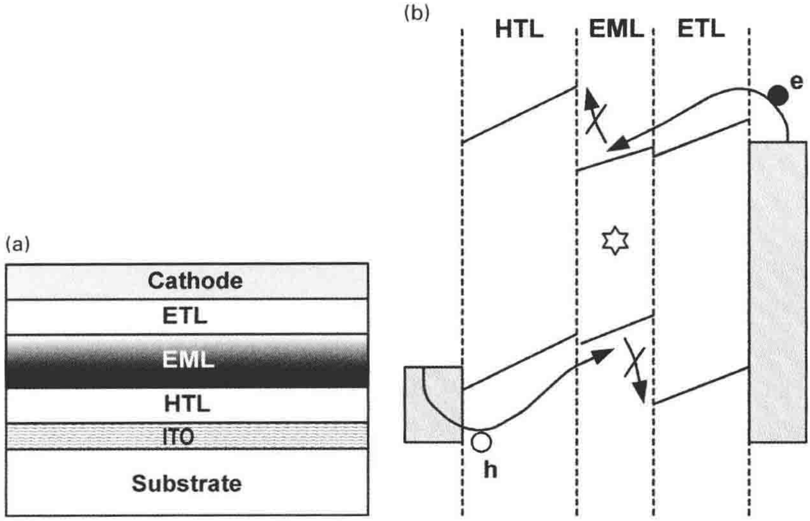

Figure 1.1 Multi-layer OLED stack structure and (b) OLED banding diagram adapted from [8, 10].

whereas, polymeric OLEDs are fabricated by spin-coating or inkjet printing [9]. However, the efficiency of small molecule OLEDs is much higher than that of polymeric OLEDs.

To increase the efficiency of the OLED, an engineered band structure is adopted [8]. A typical multi-layer OLED and its corresponding banding diagram are illustrated in Figure 1.1. The indium tin oxide (ITO) layer is the anode contact. The hole-transport layer (HTL), a p-doped layer, provides holes for the emission layer (EML), and also prevents electrons from traveling to the anode because of the band offset with the adjacent layers. For the cathode, the electron transport layer, an n-doped layer, provides electrons for the EML, and prevents the holes from traveling to the cathode. Then, the electrons and holes are recombined in the EML layer, resulting in the generation of photons [8, 10].

The luminance of OLEDs is linearly proportional to their current at low-to-mid current densities, and saturates at higher current densities.

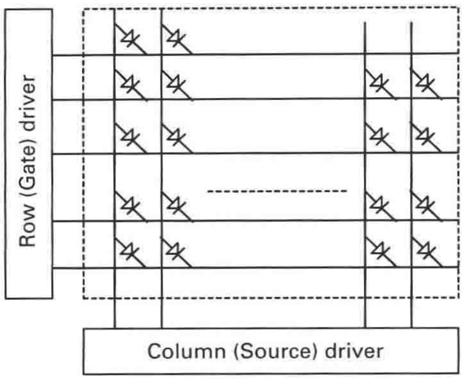

Figure 1.2 Passive matrix OLED display structure adapted from [16].

However, the voltage of OLEDs increases over time due to crystallization, chemical reaction at the boundaries, changes in the charge profile of the layer, and oxidation due to the existence of oxygen and moisture [11, 13]. Consequently, most of the proposed driving schemes are designed to provide a constant current for OLEDs.

OLEDs offer great promise in either passive or active formats. Figure 1.2 portrays passive matrix OLED (PMOLED) architecture. By applying a voltage across the appropriate row and column contacts, a specific pixel is addressed. Thereby, a current flows through the organic layers at the intersection of these contacts to light up the pixel. In this architecture, the luminance during the programming is averaged for the entire frame rate. Thus, the pixel should be programmed for $N \times L$ where N is the number of rows and L is the desired luminance for a frame [15, 16]. Thus, the OLED current density increases significantly, especially for higher resolution displays [5, 17]. Since the OLED efficiency drops at high current densities [18], to increase the display resolution, the current increases by a power law instead of linearly. Thus, the power consumption increases and the OLED ages faster. As a result, the actual applications of PMOLED displays are limited to small displays that have a low resolution [5].

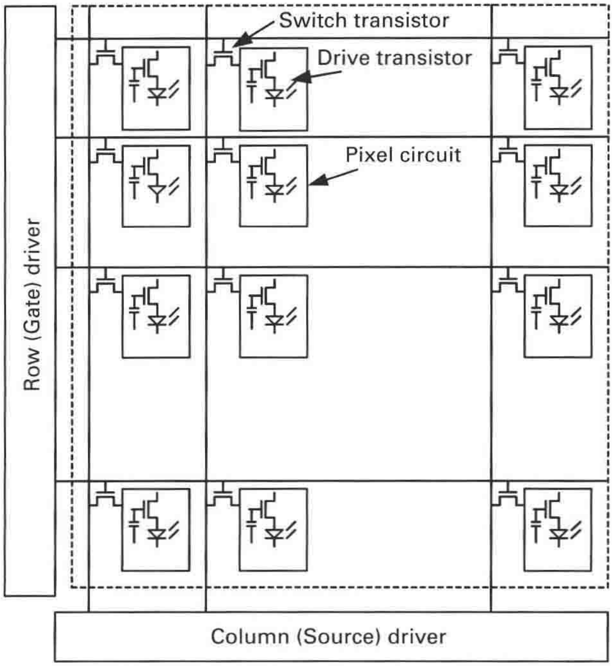

Figure 1.3 Active matrix OLED (AMOLED) display structure.

To increase the resolution and area of the displays, active matrix addressing is selected [5]. A simplified active matrix OLED (AMOLED) display structure is illustrated in Figure 1.3, where the pixel current is controlled by a drive transistor. During the programming cycle, the switch TFT is ON, and the pixel data is stored in the storage capacitor. During the driving cycle, a current, related to the stored data voltage, is provided to the OLED. Since the pixel current is smaller in the AMOLED displays, they have longer lifetimes than PMOLED displays.

Figure 1.4(a) reflects the structure of a bottom-emission AMOLED display in which the light passes through the substrate [19]. Thus the substrate is limited to transparent materials, and the aperture ratio is diminished by the area lost to the pixel circuitry, resulting in a higher current density. Moreover, the aperture ratio becomes more critical when considering a more complex pixel

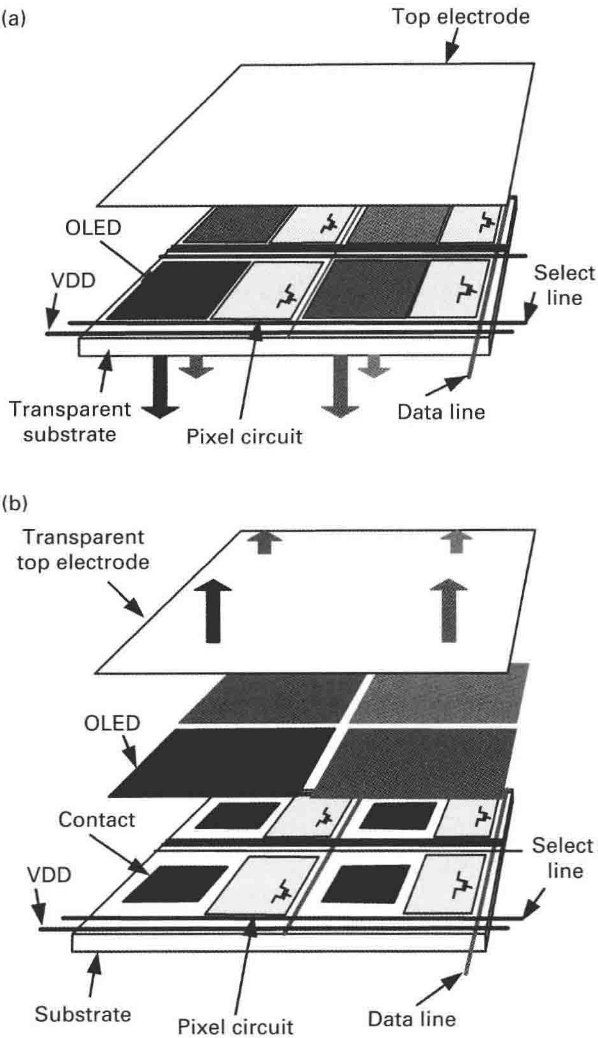

Figure 1.4 Bottom and top emission AMOLED pixel structure. Color versions of these figures are available online at www.cambridge.org/chajinathan.

circuit to compensate for both spatial and temporal non-uniformities. Hence, top-emission displays are preferred (see Figure 1.4(b)). It provides for more than an 80% aperture ratio, and the substrate is not required to be transparent [20].

1.2 Flat-panel biomedical imagers

Large-area flat-panel digital imaging has been valued for its advantages, including the separation of detector, image storage, and display, which facilitates independent improvement by isolating the complexity of the different parts from each other. Moreover, it enables the use of digital processing of the captured images to improve visual quality and to make feasible the use of computer-aided diagnostics [2, 21, 22]. The basic blocks of a flat-panel imager include a sensor and a readout circuitry using transistors which act either as a switch or as an amplifier. The sensor, commonly used in these applications, is a PIN or a MIS diode in the case of indirect detection (in which X-rays are converted to optical signals by phosphor layers) or amorphous selenium for direct detection (whereby the incident X-rays are directly converted to electrical charge).

Figure 1.5 shows a passive pixel sensor (PPS) architecture in which the pixel consists of a switch TFT and a capacitor. The charge generated by the sensor is integrated into the storage capacitor, which is read out by a charge-pump amplifier, while the switch TFT is ON. The gain of the PPS pixel is given as

$$V_{out} = Qt_{int}C_g. \tag{1.1}$$

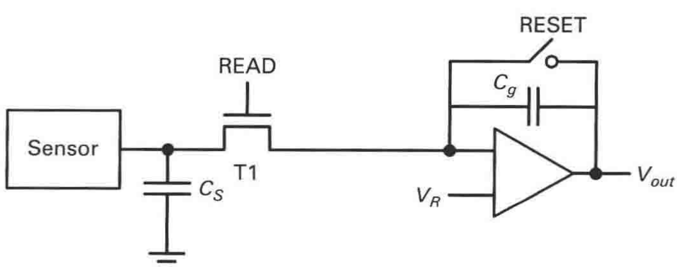

Figure 1.5 PPS imager pixel circuit adapted from [1, 2].

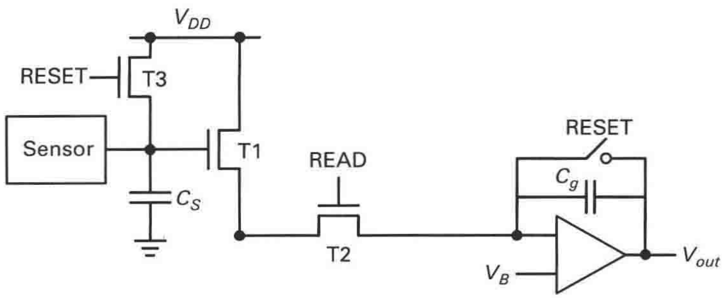

Figure 1.6 3-TFT APS imager pixel circuit adapted after [3].

Here, Q is the charge generated by the sensor and t_{int} the integration time. However, due to non-uniformities such as noise and leakage currents, the minimum level, detectable by PPS pixel, is limited.

To improve the sensitivity to small intensity signals, an active pixel sensor (APS) was introduced by Matsuura [3] (see Figure 1.6). Here, the storage capacitor is charged to a reset voltage. Then, the collected sensor charge into the storage capacitor modulates the current of the amplifier TFT (T1) as

$$I_{px} = g_m Q t_{int} \quad \text{and} \quad V_{out} = C_g I_{px} t_{read}, \tag{1.2}$$

in which g_m is the trans-conductance of T1, and t_{read} the time associated with the readout cycle. However, for high-intensity input signals, the on-pixel gain saturates the readout circuitry. In particular, for biomedical X-ray imaging applications, the significant contrast in the signal intensity of the different imaging modalities mandates unique pixel design.

Recently, hybrid mode pixel circuits have been reported that can operate between the passive and active readout for modalities employing high and low X-ray intensities, respectively. Figure 1.7 shows the 3-TFT hybrid pixel circuit presented in [23]. The issue with this type of a circuit is that it can be optimized for only active or passive operation. For example, in the active readout mode, a small storage pixel is required to improve the SNR [23], whereas, in the passive readout, a