1. Introduction

Since Tang and van Slyke demonstrated the first efficient organic light emitting diode (OLED) in 1987 [1], electroluminescent devices for lighting and display applications have received considerable interest owing to their low power consumption, large viewing angle, high contrast and compact design. In addition, OLEDs can be engineered for use as highly transparent devices across the visible spectrum of light. Based on these advantages, it is envisioned that OLEDs will provide the technological platform for the next generation of see-through displays.

1.1. Organic Light Emitting Diodes

An OLED is composed of multiple functional organic thin films which are sandwiched between two electrodes. In a conventional OLED structure, as illustrated in Figure 1.1 (a), a transparent conductive oxide (TCO) serves as the bottom anode while a metal layer is used as the top cathode. Applying an external voltage leads to hole injection from the anode into the hole transport layer (HTL). At the same time, electrons are injected from the cathode into the electron transport layer (ETL). The injected charge carriers flow toward the emission layer (EML) where they form so-called excitons. The radiative decay of these excitons leads to an emission in the visible region. The generated light is coupled out through the TCO and glass substrate. OLEDs offer a low operating voltage and a low power consumption. By using phosphorescent emitting materials, very high efficiencies of 130 lm/W with operating voltages of 2.5 V can be achieved [2]. In this work, an inverted OLED structure was employed in the development of transparent devices. Figure 1.1 (b) shows that in this case the TCO cathode is placed on the substrate and the anode forms the TCO top contact. In this configuration, the generated light is extracted from both the bottom and top contact. Since organic semiconductors provide a large Stokes shift along with low intrinsic absorption losses, highly transparent devices across the visible spectrum can be realized.

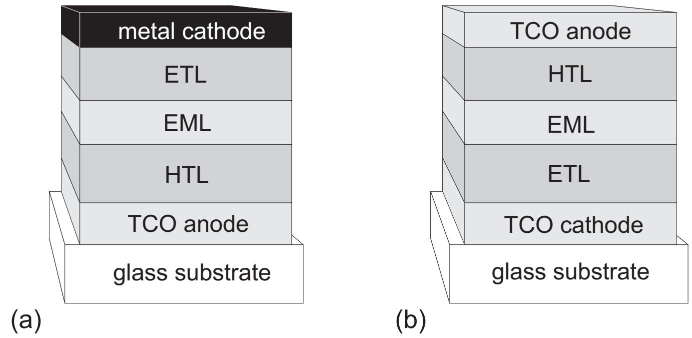

Figure 1.1.: Scheme of a conventional OLED structure (a) and an inverted transparent OLED structure (b).

1.2. OLED Displays

Today, many different display technologies are commercially available. Currently, the most prominent of theses technologies are liquid crystal displays (LCD) and plasma display panels (PDP). These technologies are not applicable, though, in the setup of a transparent display. There are only a few concepts which are viable for the realization of a transparent display. These are head-up displays (HUD), electroluminescence (EL) displays and OLED displays. With HUDs, the information is projected into the viewer's field of vision. It is an established technique which is available as head or helmet mounted display or as a fixed implementation, e.g. in aircraft cockpits. The information is projected in an optical combiner which reflects the light to the viewer. A LCD or LED systems are often used as the projection unit. The system is designed to produce a virtual image within a distance of several meters so that there is no need to refocus the eye when switching between reading the HUD information and looking through the display [3]. A major drawback of HUD technology is its elaborate optical system which is responsible for its high acquisition costs. This hampers its employment in a variety field of applications. EL displays are thin film emissive displays which consist of a multilayer structure of TCO/insulator/phosphor/insulator/TCO. When a voltage is applied, electrons can tunnel from the TCO electrode into the phosphor material. At a sufficiently high internal electric field, the kinetic energy of the injected electrons activates the luminescence center by an impact ionization. This luminescence center relaxes by emitting photons in the visible range. The advantages of EL displays are their wide viewing angle, long lifetime and compact design. Severe side effects of the technology are its high operating voltage of around 200 V and its low attainable brightness levels of around 100 cd/m^2 [4, 5]. Thus, EL displays are very inefficient. The OLED technology appears to be a more attractive alternative than the HUDs or EL displays, since the OLED combines all the important

features required for the realization of a qualified transparent display without the drawbacks mentioned earlier. OLEDs are very thin, less than 300 nm, and can be deposited on arbitrary substrates such as plastic foil. Cost-effective large area deposition techniques such as thermal evaporation or spin-coating are also available. The emissive devices offer a wide viewing angle, a high efficiency and therefore, a low power consumption. Moreover, OLEDs provide the technology for the attainment of full color high resolution displays.
To operate an OLED display, there are principally two types of addressing schemes, the passive-matrix (PM) and the active-matrix (AM) approach. In a PM display, the OLED is sandwiched in between columns of ITO and rows of metal which are arranged perpendicularly to form a matrix scheme. In this manner, each pixel is defined by a point of intersection. The PM display is scanned row by row within the frame time. Thereby, each pixel illuminates as long as the row is addressed. In this multiplex scheme, the duty cycle is inversely proportional to the number of rows N of the display. Consequently, to obtain an impression of average luminance L_m for the viewer, each pixel has to be excited with a peak luminance of $L_m \times N$. For a VGA display, a peak luminance of 72,000 cd/m^2 is needed to provide an average luminance of 300 cd/m^2 [6]. This leads to high stress on and a reduced lifetime for the OLEDs. Therefore, PM-displays are only suitable for low information content applications. On the other hand, in an AM display, all pixels can be illuminated at the same time. An AM addressing scheme for OLEDs consists of at least two thin film transistors (TFT) and one capacitor. The principle of this addressing scheme is shown in Figure 1.2. When a pixel is selected, the transistor T1 switches on. Then, via the data line, a voltage is stored on the capacitor C and the gate of transistor T2. In this mode, a current is supplied to the OLED during the entire frame time. In the following row scan, the data voltage is either refreshed or discharged. In the AM addressing mode, a much smaller current is, therefore, needed to operate the OLEDs. Thus, the AM displays allow for large area high resolution applications. Since, TFTs recognize certain variations, three or more transistors are generally used to compensate for the threshold voltage over large area panels [6, 7].

For see-through displays, not only the OLED but also the driver circuit needs to be highly transparent. Currently, established materials for TFT backplanes are amorphous-Silicon (a-Si) and polycrystalline-Silicon (poly-Si). However, Si backplanes are applicable as drivers for transparent displays only to a limited extent, since they are opaque in the visible part of the spectrum. By putting a transparent OLED next to the driving circuit, a semitransparent AM OLED display could be realized with reasonable transparency of around 20-30% in the visible spectrum [8]. Another drawback in this configuration is its low obtainable filling factor of only 30-40%. Transparent organic TFTs have also been evaluated. However, their performance is still very low [9]. Alternatives are transparent TFTs based on the wide-bandgap oxide

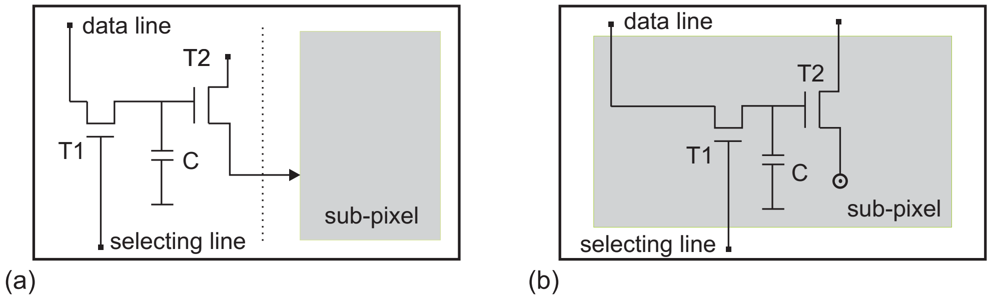

Figure 1.2.: Scheme of an OLED integration on a TFT driver circuit. (a) Horizontal integration. (b) Vertical integration.

semiconductor ZnO. ZnO TFTs showed high mobilities of up to 10 cm^2/Vs which render them for video applications. A transparent OLED can be vertically integrated onto the transparent driver circuit as shown in Figure 1.2 (b). Thus, the high filling factor enables high resolutions due to a sizable integration level. Furthermore, the inverted structure, with its bottom cathode electrode, allows for the integration of OLEDs with more powerful n-channel in contrast to p-channel TFTs.

1.3. Aims and Outline

This work is dedicated to questions related to the realization of efficient transparent OLEDs for AM displays. The focus lies on device concepts which are reliable, cost-effective and compatible with standard production techniques. In order to accomplish this, a deeper understanding of the physical and chemical modes of operation is needed and will be presented.

The individual topics are organized in the following manner:

To begin with, the fundamental physics of organic semiconductors and OLED devices are described in Chapter 2. In Chapter 3, the applied deposition techniques and the analytic methods are introduced. A discussion of the experimental results is given in Chapter 4. First, the damaging effects of an ITO sputtering process on top of an OLED were studied by SIMS and transport analysis. Hence, specifications of appropriate buffer layer are discussed. Then, the particular benefits of vertical stacking by charge generation layer for transparent OLEDs are evaluated. The chapter ends with the description of the first demonstration of a transparent active-driven OLED pixel.
Chapter 5 introduces transition metal oxides as being very effective in their use as a buffer layer against damage from plasma assisted deposition processes such as sputtering and pulsed

laser deposition. It will be shown that MoO_3 and WO_3 possess all the specifications required to qualify as an effective buffer layer for transparent OLEDs. The structural properties of the buffer layer were studied by employing AFM and TEM methods. Moreover, the penetration depth of ITO into the buffer layer was estimated by using SIMS analysis. Highly efficient devices were shown to possess an average transparency of more than 75% in the visible spectrum. Furthermore, indium-free OLEDs offering extremely low leakage currents were realized.

Chapter 6 is dedicated to WO_3 p-type doping of organic hole transport materials with deep lying HOMO levels in the order of 6 eV. The doping effect was studied by optical spectroscopy and transport experiments. Design rules for OLED devices having a p-type doped layer are expounded in this chapter. It concludes with a discussion of strategies for enhancing the directed light extraction from a transparent OLED.

Finally, in Chapter 7, the thin film encapsulation prepared with ALD at a temperature of 80 °C is discussed. Specifically, neat Al_2O_3 films are introduced and studied as an optimization step in very dense permeation barriers based on Al_2O_3/ ZrO_2 nanolaminate structures. It will be shown, that the alternating nanolayer allows for pin-hole free thin film encapsulation which is suitable for large-area organic devices.