1. Introduction

Organic light emitting diodes (OLED) represent an important emerging technology for flat panel displays and solid state lighting [1,2]. The fast-paced development of mobile electronic devices demands for thin, light-weight and power-efficient display panels. So far, the need for mobile or desktop flat panel displays (FPD) was mainly satisfied by liquid crystal displays (LCD), which are further expected to take over the market leadership in the large panel segment within the near future. OLED technology promises further weight and power savings, a larger viewing angle, higher brightness levels and an increased contrast ratio, but still lacks in terms of reliability and suitable mass production equipment. This work contributes to the development of device and process technology for high-resolution full color OLED displays.

1.1. organic light emitting diodes

First reports on organic electroluminescence in vacuum-deposited or spin-coated thin film devices [3,4] excited intensive research activities on organic light emitting devices within the last two decades. One of the decisive achievements compared to earlier reports [5] was, that a significant light output could be measured at very low operating voltages of about 10 V or less. The proposed OLED structure complies with the functional schematic displayed in figure 1.1.
The significant difference to prior work is, that a heterostructure consisting of a mainly

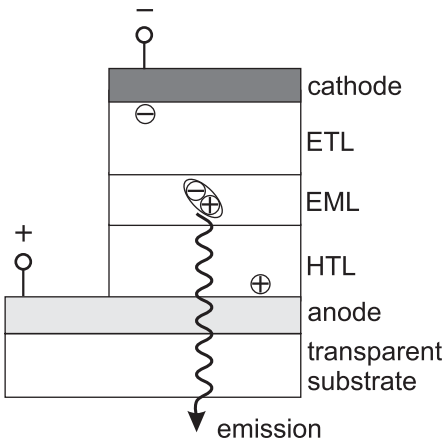

Figure 1.1.: Working principle of organic light emitting diodes, as proposed in reference [3].

electron transporting material and a mainly hole transporting material is employed. When an external voltage is applied, electrons are injected from the metallic cathode into the electron transporting layer (ETL). Correspondingly, the transparent indium tin oxide (ITO) anode injects holes into the hole transporting layer (HTL). Often a dye-doped ETL or HTL is employed as emission layer (EML). Recombination of charge carriers occurs within the EML at the heterointerface between the ETL and HTL and leads to the formation of excitons. The radiative decay of excited states can be observed by the light, which is emitted through the transparent substrate. Today, highly efficient OLEDs employ phosphorescent emitter materials and yield external quantum efficiencies of up to 29 % [6].

1.2. OLED-displays

In the past two decades, research on organic light emitting diodes was driven by the idea of realizing outstanding flat panel displays. In principle, two possible ways of realizing OLED displays can be pursued. The first generation of commercially available OLED displays employed a passive-matrix (PM) driving scheme. These displays are used in low information content sub-displays for mobile or automotive applications. Currently, the next generation of OLED displays is developed, which are driven by an active-matrix (AM) backplane. Both driving schemes shall be briefly outlined.

1.2.1. passive-matrix OLED displays

In a passive-matrix OLED display, single pixels are defined by the intersection of patterned anode rows and cathode columns. Usually the anode consists of a transparent conductive oxide (TCO), for example indium tin oxide (ITO), which can be patterned by photolithography and wet-chemical etching. Since the organic materials are very sensitive to solvents and etching agents, the cathode columns cannot be patterned via photo-lithography. The patterning task is therefore solved by evaporating the metal cathode either through a thin shadow mask or onto a pre-patterned photoresist layer with deeply undercut edges at which the organic layers and the metal film separates into columns [7,8].
During operation, only one anode row is addressed at once and the brightness level of each pixel of this row is determined by the current, which is imposed onto the corresponding cathode column. Leakage currents, which may lead to crosstalk between different rows, are suppressed by applying a reverse bias onto all rows except the one, which is currently addressed. In the described multiplexing scheme, the fraction of on-time is inverse proportional to the number of anode rows. As a consequence, a peak luminance of more than

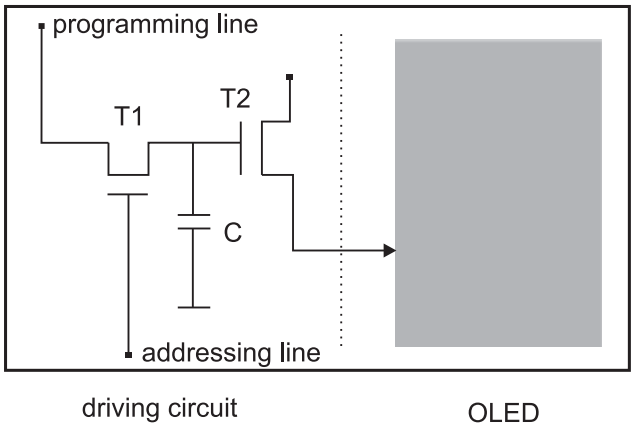

Figure 1.2.: AM-OLED pixel: Horizontal integration of TFTs and bottom-emitting OLEDs.

24000 cd/m^2 is necessary, to achieve an average brightness of 100 cd/m^2 for a quarter-VGA resolution (320 x 240 pixels) [9]. At such high brightness levels, the increased driving voltage and resistive respectively idle losses due to charging and discharging of the anode and cathode lines dramatically reduce the overall system efficiency. Model calculations for quarter-VGA PM-displays showed, that an initial OLED efficiency of 10 lm/W is reduced to a system efficiency of about 0.2 lm/W [10], which suggests, that PM-OLED displays will not be suitable for high-resolution full-color OLED displays.

1.2.2. active-matrix OLED displays

Due to resolution limitations, which arise from the high peak luminance in PM-OLED displays, it is favorable to apply an active driving scheme, which permanently supplies the necessary driving current to the OLED. Corresponding to this need, a large number of reports on silicon-based [11–13], organic [14–16] or even highly transparent, ceramic [17] thin film transistors (TFT) integrated onto OLED substrates was published. It is most likely, that existing polycrystalline or amorphous silicon technology will be used for the first generation of commercial AM-OLED displays.
For controlling the OLED current, at least two transistors have to be employed in AM driving schemes, as depicted in figure 1.2. The displayed pixel is addressed via transistor $T1$. When switched on, a gating voltage for transistor $T2$ is programmed onto the store capacitance C. If C is charged, the transistor $T2$ is switched on and the pixel is illuminated. Discharging of the capacitance switches off the current flow through $T2$ and the pixel remains dark. Driving circuits, which consider gray-scaling and threshold voltage compensation, commonly use 3 or more transistors per pixel [9, 13, 15]. In a bottom emitting architecture, the OLED has to be placed beside the driving circuit to allow the generated light to be emitted through the substrate. This inherently limits the filling factor, which is defined as the ratio of light

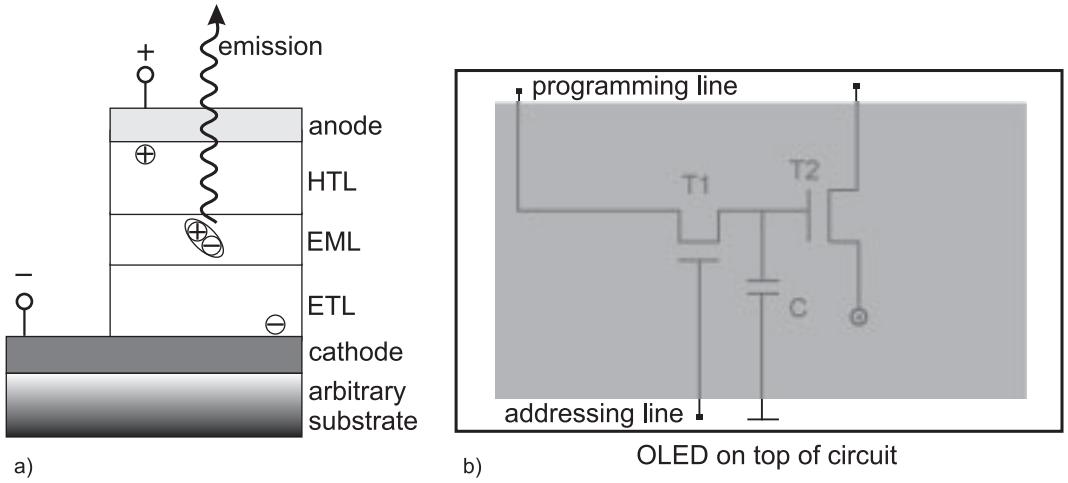

Figure 1.3.: AM-OLED pixel employing an inverted OLED design: a) Structure of an inverted organic light emitting diode. b) Vertical integration of TFTs and top-emitting IOLED.

emitting to total pixel area. In general, a filling factor of 30 - 40 % is suggested for bottom-emitting AM-OLED architectures, which turns out to be a fundamental drawback.
Higher filling factors can be achieved by employing top-emitting OLED concepts. These are conventional OLEDs emitting light through a transparent or semi-transparent cathode [18–22] and inverted organic light emitting diodes (IOLEDs) [23–25] with sputtered ITO top-anodes. In the latter case, more effective n-channel TFTs can be used for the AM-backplane [9]. Figure 1.3 depicts the inverted device concept, which demands for a reversed deposition sequence. Now, the light is emitted through the transparent top anode, which allows vertical integration of the light emitting device on top of the AM driving circuit and significantly increases the filling factor. The inverse deposition sequence implies several technological challenges, of which sputtering of ITO on top of sensitive organic layers is identified as the most severe task. Polymeric or molecular polycrystalline buffer layers were introduced to prevent from sputter-induced damage [24–26]. The reversed layer sequence also affects charge injection from the electrodes, which can be improved by applying doped charge injection layers [25]. Although the preparation of IOLEDs underlies certain limitations, the benefits for AM-OLED displays makes IOLEDs appear as a promising and important topic for further research activities.

1.2.3. production issues

So far, the OLED technology did not fulfill the predicted expectations for the display market. To some extent, this can be explained by the lack of mass production equipment and the incompatibility of several preparation processes to production demands. For commercial success, the production of OLEDs must be as cost-effective and reliable as it holds for todays LCD production, which sets the standards as dominating technology. Several of the front- and back-end processes can be adopted under minor efforts. For example, the cleaning of the substrates and packaging of finished devices are referred. A major difference in the process chain arises, when the deposition of organic materials is concerned. Several different approaches for high-yield, high-throughput deposition of OLEDs were introduced in the past. Among these are thermal evaporation from multiple point sources within cluster-type OMBD tools, ultrahigh-rate organic vapor phase deposition within a single reactor [27, 28], and thermal evaporation from linear sources within an inline configuration [8, 29]. In the LCD production, inline sputtering of ITO already proofed its reliability under high-throughput conditions. Therefore, it is reasonable to employ inline deposition systems for mass production of OLEDs. Due to the nonexistence of suitable co-evaporation sources and patterning technologies for substrate sizes exceeding $1\,m^2$, further efforts have to be carried out until large AM-OLED screens will be commercialized.

1.3. goals and outline of this study

This work is motivated by the development of device and process technology for full-color AMOLED displays. It is expected that the application of phosphorescent emitter materials will significantly increase the efficiency of inverted organic light emitting diodes. In the course of this study, a stacked device concept for IOLEDs is proposed and will be intensively examined. A second emphasis is placed onto the development of inline deposition processes and equipment. Concerns are focused on room-temperature sputtering of ITO, co-evaporation of organic materials and patterning technology.

The presented study can be outlined as follows:

Chapter 2 starts with an introduction to basic models describing charge injection, charge transport and recombination in organic light emitting diodes. Following, a brief summary of device preparation and characterization is given in chapter 3.

In Chapter 4 experimental results for inverted organic light emitting diodes employing highly efficient phosphorescent materials are discussed. The discussion comprises the identification

of quenching mechanisms and possible ways to minimize these, which leads over to the realization of highly efficient red, green and blue IOLEDs.

Next, stacking of OLEDs as a new device concept is demonstrated (Chapter 5). A physical model of the charge separating mechanism at doped organic pn-junctions is drawn from experimental data obtained by Kelvin Probe measurements and temperature- ,respectively thickness-dependent current voltage characteristics. It will be shown, that the application of the stacking approach to inverted OLEDs yields an outperforming device efficiency.

The development of inline deposition processes and equipment is presented in chapter 6. The chapter starts with a discussion of the influence of oxygen flow and RF power ratio on the optical and electrical properties of room temperature (RT) sputtered ITO.
Further, a unique design of a linear co-evaporation source is visualized and evaluated by thickness and concentration distributions of thin films deposited onto large substrates.
To the end of chapter 6, the laser induced local transfer of organic emitter materials is proposed as novel, high-resolution patterning technique for full-color OLED displays. The process will be described by a physical approximation. The approximated model will be confirmed by comparison to the experimental results.