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OLED manufacturing for large area lighting applications

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ABSTRACT

We present first results of a new developed large area manufacturing system for organic light-emitting diodes (OLED) dedicated to lighting and signage applications. The system combines high throughput with flexibility in production at highly-precise deposition conditions. After introducing the system with its modules, first results for organic and metal layer deposition properties are shown. Next orange/red p–i–n type OLED samples are prepared on large ITO substrates and the characterization by luminance and current measurements are presented. The devices achieve very high efficiencies up to 31 cd/A on large area substrates which are comparable to devices on smaller substrates.

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1. Introduction

Organic light-emitting diodes (OLEDs) have made great progress since the first presentation of thin film devices based on small molecule organic materials by Tang and VanSlyke in 1987 [1]. The OLED performance and stability have been rapidly increased over the last years [2]. Also, the size of the devices is growing and several applications like displays [3] and general lighting [4] are produced. The developments for lighting applications will reach high efficiencies and low cost production to replace fluorescent and phosphorescent lamps [5]. Because of very thin active layers (several 10–100 nm), the low material amount used for the production of OLED results in cheap and lightweight products.

Stable deposition conditions are necessary for accurate thin film depositions of organic semiconductors. Layer thickness homogeneity better than $\pm 5\%$ allows a uniform distribution of optical and electrical OLED properties over the whole substrate area.

Mass production of high efficient OLED on larger area is still a challenge. To show the scalability of OLED process technology for larger substrates and high throughput, a new deposition system was specified by IPMS and provided by Sunic Systems, Inc. It is designed for OLED signage and lighting application and doesn't need high accuracy shadow masking as used for RGB display manufacturing. Two more advantages should be mentioned: long up time of several days of production without any maintenance and a low tact time down to 3 min to reach a high throughput of substrates.

The general process flow for the production of an OLED can be subdivided in different steps. The first step is the anode layer deposition on top of the bare glass typically done by sputtering of a thin conductive oxide (TCO) and structuring by a photolithography process. The requirements for TCO-coatings for OLED applications can be summarized by high transmission (>90%), low sheet resistance of 1–50 Ω/sq, high work function (~5.0 eV) and low roughness below 1 nm (RMS). Additionally a passivation layer is deposited optionally and structured to prevent a shorting between anode and cathode wire crossings. Several cleaning steps are applied to remove residuals from the anode surface. Before the vacuum process starts, the adsorbed water will be removed by an annealing step at inert conditions. Directly connected, the plasma pre-treatment process and the OLED stack deposition are performed and closed with the transfer to the encapsulation system. The encapsulation is done by covering the active area with an additional glass to protect the sensitive OLED structure from atmospheric conditions. But a more and more interesting process is a thin film encapsulation (TFE) [6] by the deposition of a barrier layer to produce thinner devices.

This work focuses on the investigation of the ITO anode layer and presents the results of vacuum processes to deposit organic and metal layers for OLED devices with the new manufacturing tool (Fig. 1). The achieved OLED device characteristics on large substrates are comparable to diodes produced under laboratory conditions.

2. Experimental

The manufacturing system is based on different clusters including process modules for pre-treatment, organic layer deposition, metal deposition and automatic transfer to an encapsulation system. A substrate with the size of 370×470 mm^2 (or so-called "GEN2"-size) is used and the transfer is done by robot handlers fully automated. After loading, the substrates are annealed in an oven chamber to reduce the adsorbed water. Afterwards the pre-cleaning module removes organic residuals from the substrate surface by combined argon/oxygen

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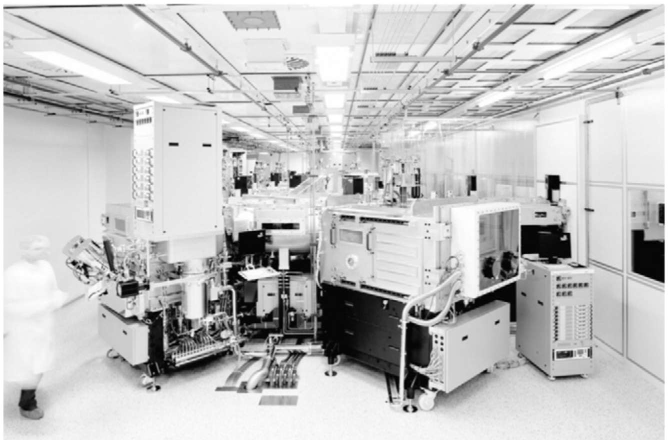

Fig. 1. View of large area OLED deposition tool.

plasma that is generated by an ICP (ion coupled plasma) source under vacuum conditions. The plasma process also increases the work function of indium–tin oxide (ITO) [7].

The cluster system contains five process modules for the organic and two for the metal layer depositions. These modules are equipped with point sources optimized for high layer homogeneity. Their base pressure is below 10^{-7} mbar to generate high purity layers. A p–i–n OLED device structure [3] consists of a p-doped hole transport layer (p-HTL), an electron blocking layer (EBL), an emitter doped emission layer (EML), a hole blocking layer (HBL), a n-doped electron transport layer (n-ETL) and an aluminum cathode. The layer thicknesses of EBL, EML, and HBL range between 10 and 20 nm. The HTL and ETL are co-evaporated layers containing a host as matrix material and an electrical dopant. The emitter layer bases on a phosphorescent orange/red dye embedded in the host material (see Ref. [8]). The p–i–n OLED technology was provided by Novaled AG [9].

The system is designed to reach a tact time of 3 min which implies an output of one substrate every 3 min. It is able to use rigid glass substrates or flexible sheets. The substrates used in this work are float glass coated with indium–tin oxide (ITO) and structured by photolithography and wet etching processes (substrates supplied by Thin Film Devices) without passivation and metallization layers. The cleaning of the structured ITO substrates is done by surfactants and DI-water before the processing.

The film uniformity data of the organic layers are measured by a VASE system (variable angle spectroscopic ellipsometry, J. A. Woollam Co., Inc.) to determine optical data including thickness information at different points on the substrate [10]. Morphology is investigated by non contact mode atom force microscopy (AFM) (Nanoscope D3100, Veeco). The luminance and current vs. voltage characteristics are carried out using a DMS 401 system (supplied by Autronic-Melchers).

3. Results

3.1. Properties of the thin films

The analysis of the ITO surface is done by AFM and shows a grain structure with smooth surface. The measured R_q (RMS) value is only 0.6 nm and the maximum peak (R_{max}) value represents 12.0 nm. An AFM micrograph is shown in Fig. 2. The measured low roughness values are sufficient for the deposition of thin organic layers. The sheet resistance is measured by a value of ~35 Ω/sq.

To proof the deposition homogeneity of organic films, the material tris(8-hydroxy-quinoline) aluminum (Alq3) is evaporated at two different deposition rates (Fig. 3). Typically rates for the host materials are 2.0 Å/s and for the dopants 0.5 Å/s. Measurement points are set diagonal on the substrate area to see the largest deviation [11].

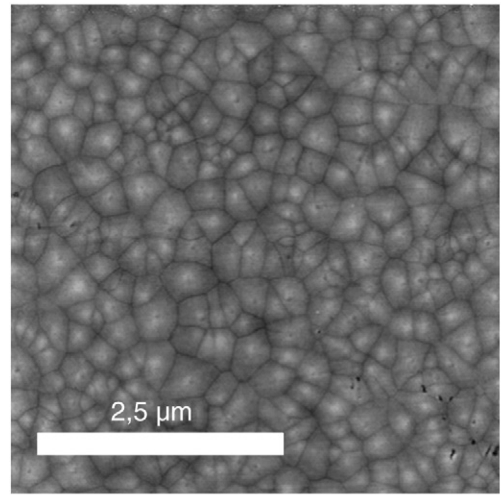

Fig. 2. AFM micrograph of the electrode ITO film on glass.

Excellent thickness homogeneity is determined for both, low and high deposition rates. The variation for the host material is at 1.7% and for the dopant at 2.9%. The set point for the thickness is 100 nm in both cases but a slight drift of +1.5% and −2.2% respectively, is observed. Together with the homogeneity results it is sufficient for high-precision and stable rate OLED deposition processes.

Aluminum is used as cathode material for the OLEDs. It is evaporated from crucibles at two different rates. The morphology of the surface is investigated by AFM measurements (Fig. 4). The sample preparation is done on cleaned bare glass by an evaporation of 100 nm thick aluminum. The roughness and maximum peak values for the aluminum coating at the two rates are nearly independent from the rate and summarized in Table 1. The achieved low roughness data of the aluminum coatings are sufficient for the cathode deposition on smooth organic layers to realize the second electrode of an OLED.

3.2. OLED devices

After the investigation of the single deposition processes shown above, materials for a p–i–n type OLED are installed. The deposition rates are constant at 2 Å/s for the host materials and respectively lower for the dopant materials. For the aluminum layer the deposition rate is adjusted to 12.5 Å/s. These values for the deposition rates are identical to the previous experiments with single layers. The layer

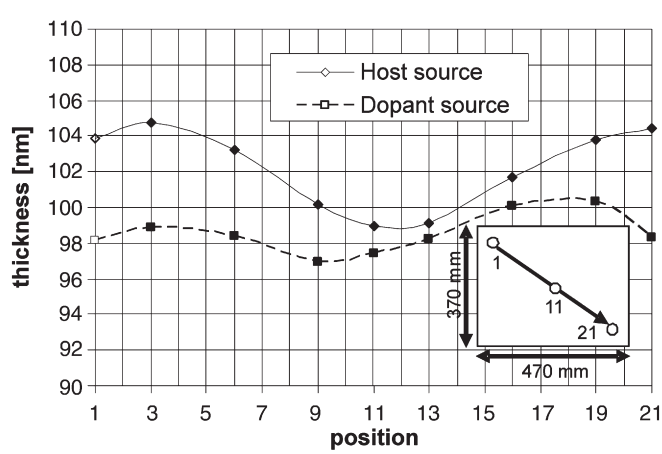

Fig. 3. Layer homogeneity of Alq3 layer deposition for host and dopant source by VASE ellipsometry.

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