

Roll-to-roll deposition for Organic Light Emitting Diodes (OLED)

Stefan Mogck, Christian May

Stefan.mogck@ipms.fraunhofer.de

Phone: 0049(0)351 8823235, Fax: 0049(0)351 8823266

Fraunhofer-Institute for Photonic Microsystems

Center for Organic Materials and Electronic Devices Dresden (COMEDD)

Maria-Reiche-Straße 2, D-01109 Dresden, Germany

www.ipms.fraunhofer.de

Abstract

OLED technology has successfully penetrated the display market within the last years. To enable OLED technology for further markets like signage and general lighting, cost reduction is a major issue. The use of ITO coated glass substrates as used for passive matrix displays is therefore not an option for lighting application. Low cost metal foil as substrate for the deposition of organic light-emitting diodes in combination with the p-i-n OLED technology will allow a major cost reducing step. Furthermore there is a need to replace sheet to sheet fabrication technologies by roll-to-roll-processing. Within the “Center of Organic Materials and Electronic Devices Dresden” (COMEDD) of Fraunhofer IPMS a roll-to-roll line for research and development in OLED lighting is currently going into process.

Introduction

The power consumption plays more and more a dominant role for light sources, because conventional filament light sources transfer a fraction of electrical power for lighting. An alternative for higher efficiencies are fluorescent lamps, but they consist of, for the environment toxic mercury. In the recent years, light emitting diodes (LED) lamps become commercial available, but fluorescent and LED lamps emit more the cold white light. Light emitting sources based on organic materials are therefore the most promising technologies, because they are flat, without toxic mercury and produce light of high quality in high degree of freedom for the emitting spectrum.

Organic light emitting diodes (OLED) create light from thin films by applying a voltage of 4 –5 V between two electrodes. Between the electrodes thin layers of several 100 nm of organic compounds convert the injected charge into photons through the formation and subsequent recombination of excitons. OLED devices are integrated in display devices with much less power consumption compared to liquid crystal devices, because no backlight is needed for organic lighting systems. OLED technology has successfully penetrated the display market within the last years.

In general, OLED systems emit less light per area compared with LED devices which are more capable for point sources. OLED can be used for area illumination on large area panels. In the recent years progress has been made to develop large light panels on transparent ITO (indium tin oxide) coated glass substrates [1], [2] and [4]. However the price for ITO has been increased over the last years significant. An alternative transparent electrode to replace ITO for organic light emitting diodes have been successfully developed [5]. For lighting application,

like signage and general lighting cost reduction is a major issue. Therefore ITO based OLED systems are not an option in the future for lighting applications.

OLED on rough metal substrate

Low cost metal foil as substrate for the deposition of organic light-emitting diodes will allow a major cost reducing step. Instead of using ITO as an electrode material, the OLED can be directly deposit on the conductive metal foil. A disadvantage of metal foils is the roughness and higher defect densities, like scratches due to the fabrication process of the metal foils. Table 1 gives an overview of the RMS surface roughness and maximum peaks for silver coated glass, aluminum foil and ITO coated glass determined by AFM.

Table 1. Surface roughness on different materials

Substrate	RMS (nm)	Roughness peak (nm)
Al foil evaporated with 200nm Ag	2.5	25
Glass evaporated with 200 nm Ag	2,6	22
Glass substrate with coated ITO	≈1	< 10 nm

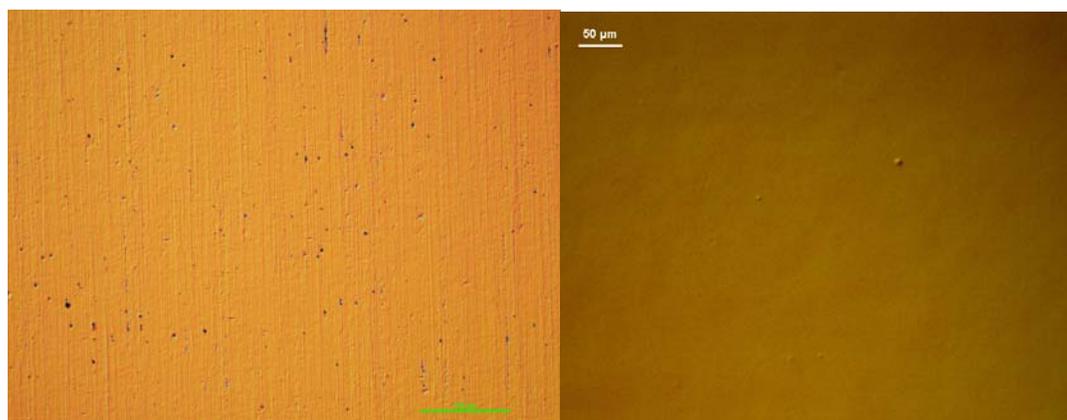


Figure 1. Optical images of surfaces of an untreated aluminum foil with a non-conducting smoothing lacquer and not cleaned, see left image. The right image shows the same type of aluminum foil, but cleaned and coated with silver. The left image shows clearly the texture

Substrate defects and high roughness peaks initiates short cuts and high leakage currents in the OLED devices. Therefore smoothing and cleaning pre-treatment are necessary to improve the surface properties of the metal foils, see figure 1. In the future an attempt will be made to manufacture OLEDs directly on commercial available metal sheets in a roll-to-roll process.

For OLED on metal foils only top emitting systems are possible due to the intransparency of metal foils. In top emitting OLEDs micro cavity effects play a dominant role compare to bottom emitting OLED on glass. Therefore a precise thickness tuning of the individual organic layers is needed to reduce the micro cavity effects and maximize the light out coupling and the efficiency of the OLED devices.

At present two different OLED technologies have been preferred: Polymeric light-emitting diodes (PLEDs) can be fabricated using solution processing, like spin-coating or printing processes. OLED based on small molecule materials (SMOLEDs) will be deposit by evaporation in vacuum coaters. The advantage of the small molecule OLEDs with mostly phosphorescent (triplet emitter) emitting layers have higher lifetime and efficiency compared with the fluorescent (singulet emitter) PLED devices. Therefore, the SMOLEDs should be the first option for lighting and signage applications. To increase the efficiency further, a reduction of ohmic losses and an increase possible different type of electrode materials the intrinsic emitting OLED layers (*pin* OLED) will be favored [3]. The emitting layers in the *pin* OLED stack are sandwiched by doped transport layers for holes (p-layer) and electrons (n-layer), respectively. The higher degree of freedom with the *pin* OLED technology gives more possibility to fabricate high efficient OLEDs on different metal foils with minimum ohmic losses and high efficiencies. Figure 2 shows a principle design of a *pin* OLED stack.

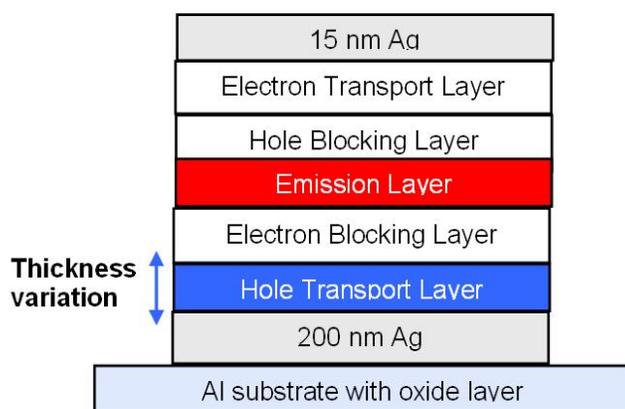


Figure 2. A principle design of a *pin* OLED stack.

By using the *pin* OLED technology it is possible to increase the thickness of the hole transport layer to the 2nd maximum without significant losses in device performance to avoid shortcuts and to get more stable devices due to the higher roughness of metal foils, see figure 2.

With the existing equipment for vacuum evaporation at Fraunhofer IPMS [4] of small molecule OLED commercial aluminum sheets were fabricated. The structuring of the metal sheets is performed by printing a non-conducting passivation layer, followed by OLED evaporation with appropriate shadow masks. Figure 3 shows first processed 2 color based white *pin* OLED stack (This even works with the 1st HTL maximum, but less device stability) on Ag coated aluminum test substrates with approximately 6 –7 cd/A current efficiency. For white top-emitting OLED devices it is a challenge to tune a proper stack for good light out coupling for the whole wavelength spectrum. In standard OLED devices, the out-coupling efficiency is approximately 20%. The rest 80% light is trapped in organic and substrate modes. Therefore there exist high potentials to increase the power efficiency by improving the out-coupling of the light. Recently, investigations have been performed to find proper additional capping layer onto the semi-transparent top contact to minimize the micro cavity effects for white light emission [6] and even the potential to exceed the power efficiency of fluorescent tubes [7].

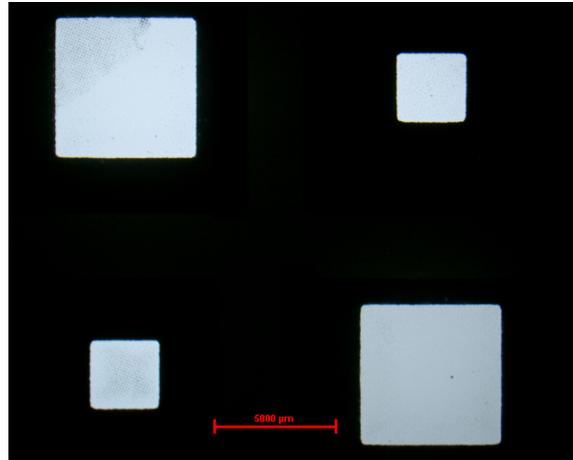


Figure 3. The image shows 4 quadrant layout on a 35 x 50 mm² aluminum sheet during an electrical test. The first HTL thickness maximum fabricates good yield data on the aluminum test sheets of around 70 – 80 %, but not sufficient device stability.

Relative thick doped transport layers allow it to get more stable devices on rough substrates. This was demonstrated on 200 x 200 mm² aluminum sheets with a green *pin* OLED, see figure 4.

	100 cd/m ²	1000 cd/m ²
η_c [cd/A]	18.0 – 20.5	15.3 – 17.0
η_p [lm/W]	20.1 – 24.0	10.6 – 15.1
η_Q [%]	4.6 – 5.3	4.1 – 4.3



Figure 1. The photograph shows a green OLED deposited aluminum sheet under electrical testing. Power efficiencies between 20 - 25 lm/W is well possible for green *pin* OLED stacks on aluminum sheets (for comparison: A 75 W filament lamp has \approx 12 lm/W).

The Roll-to-Roll Vacuum Coater

For further cost reduction it is needed to replace sheet to sheet fabrication technologies by roll-to-roll-processing. Within the project ROLLEX [8] a roll-to-roll coater (supplier Von Ardenne Anlagentechnik GmbH) for research and development in OLED lighting is currently going into process at the “Center for Organic Materials and Electronic Devices Dresden” (COMEDD) at Fraunhofer IPMS. Roll-to-roll OLED deposition of metal foils with a thickness up to 0.5 mm, a width of 300 mm will be equipped step by step with more linear organic evaporators to get white emitting OLEDs . All evaporation modules are arranged around a 2m diameter sized, water cooled, deposition cylinder, as schematically depicted in figure 5 .

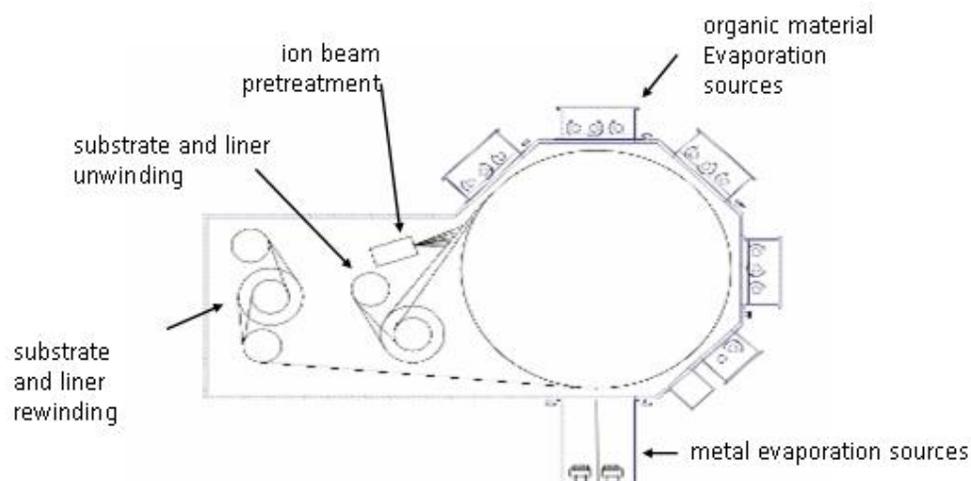


Figure 2. Schematically drawing of the roll-to-roll vacuum coater with the 2 m diameter sized deposition cylinder with the arranged deposition modules.

The patterned metal foil will be first pretreated with an argon plasma. Additionally, the deposition cylinder can be heated up to 80 °C to remove residual moisture. After the pretreatment, the organic linear evaporators deposit the organic stack onto the metal sheet. Finally, the semi-transparent top electrode and the metal contact will be evaporated on the OLED layers.

Patterned organic and metal film deposition is possible using low resolution striped shadow masks located in a fixed position in front of the substrate. Furthermore, there is a possibility to protect the metal foil against scratching during the winding process by enveloping the metal substrate with a liner foil, as illustrated in figure 5. The total volume of the process chamber of the roll-to-roll vacuum coater is approximately 6 m³ with a height of about 3 m. Figure 6 shows a photograph of the roll-to-roll vacuum coater with the open process chamber.



Figure 6. A photograph of the roll-to-roll coater with the open process chamber.

Conclusion and Outlook

High efficient top emitting OLEDs on metal foil and a unique approach for roll-to-roll vacuum processes could be illustrated.

A drawback of OLED devices, in contrast to inorganic lighting diodes, is the high sensitivity against moisture and oxygen. Therefore the OLED stack must be encapsulated with a barrier layer with low water and oxygen permeation (water $< 10^{-5}$ g/m²*d), oxygen $< 10^{-5}$ cm³/m²*d*bar). The present status lifetime of OLED systems is 10,000 – 20,000 hours using glass encapsulation. For keeping up the flexibility of the metal foil only thin film encapsulation or roll-to-roll lamination of a barrier foil can be an option as encapsulation technique. One concept of thin film encapsulation is a multilayer stack with alternating metal oxide and organic layer, e.g. [9]: The metal oxide layers have the actual barrier properties and the organic layers in between decouple the in general brittle metal oxide layers. With the multilayer approach the mechanical stress can be minimized and defect decoupling reduces the permeation.

In the near future the roll-to-roll vacuum coater will be fully equipped with 14 organic linear evaporators to get white emitting OLEDs. This allows further R&D work to develop high efficient and productive OLED lighting and organic solar cell devices. A remaining question will be the dependence of electrical parameters during scaling up the lighting areas [10] and [11] according to temperature effects, current decay across the lighting area and the leakage current. A roll-to-roll cleaning, patterning and lamination process will be the next steps to complete the Roll-to-Roll line for high efficient OLED on metal strip. Essential for a successful process integration of OLED fabricated in a roll-to-roll line are proper process monitorings. Therefore a roll-to-roll inspection system will be developed and available in the near future.

Acknowledgement

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