Vacuum based Roll-to-Roll OLED coating on pilot level

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Production of OLED display and OLED lighting modules is currently a vacuum based sheet type small molecule evaporation process. OLED manufacturing is currently on the move from rigid glass to flexible substrates and first products are commercially available. In general, such flexible substrates are bonded on a glass carrier and will be peeled off after the OLED integration process from the glass carrier. An opportunity for OLED production on flexible substrates is to consider cost effective roll-to-roll fabrication with high throughput for mass market applications. Since 2009 a roll-to-roll vacuum based OLED process line have been brought into operation at Fraunhofer FEP to develop reliable OLED process technologies to cover the complete manufacturing chain. Within the European PI-Scale initiative a goal is to establish pilot production concepts of flexible OLED devices with open access concepts for end-users. The main focus is to develop the OLED market and push business opportunities along the complete value chain. The paper will outline a roll-to-roll OLED pilot production perspective based on vacuum technology on different types of flexible substrates supported by the European PI-Scale project.

Introduction of the Roll-to-Roll OLED line at Fraunhofer FEP

The roll-to-roll infrastructure allows product developments starting with the uncoated web till to full integrated OLED lighting systems. In the following, the roll-to-roll R&D prototype line will be outlined which will be applied inside the project regarding roll-to-roll OLED fabrication.

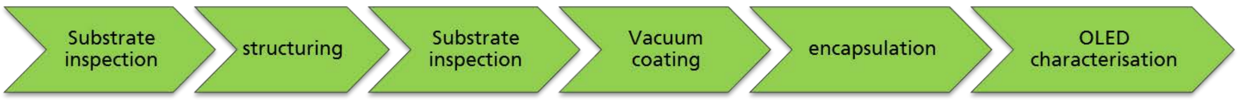

Figure 1: Process flow of the R2R prototype line from substrate inspection up to the final electro-optical characterisation of OLED devices.

For the deposition of small molecule OLED devices a unique vacuum coater have been qualified with 14 organic linear sources with alternating single, co-evaporation and triple-evaporation. This allows highly efficient OLED stacks, for e.g. *p-i-n* OLED technology with doped transport and emissive layers [1]. Meaningful efficacy and lifetime has been reached for OLED devices made by vacuum thermal evaporation process, so far.

Figure 2: A photograph of the roll-to-roll OLED vacuum coater with 14 organic linear sources, plasma source for pre-treatments, 2 metal evaporators for the electrode deposition and magnetron sputter system for pre-encapsulation with metal oxide.

After the OLED coating process the coated coils are still sensitive to moisture. Therefore, the OLED coated coil need to be transferred and encapsulated under N_2 protective environment.

Figure 3: Photograph of R2R lamination system which is encased in an inert box at Fraunhofer FEP. The butyl gloves allows still high flexibility in process variations under R&D conditions.

Figure 3 shows the photograph of the roll-to-roll lamination tool for OLED encapsulation which operates in a protective nitrogen environment with H_2O and O_2 of < 10 ppm, respectively. Additionally, the lamination system has an integrated printing unit for deposition of dielectrics and metal paste. Different type of UV units, IR dryer and a flash lamp annealing system are available for curing and drying of different coated materials.

For understanding of process- and substrate quality issues a roll-to-roll optical inspections system is available as well. The optical inspection system consists a winding unit and an inspection table. Over the inspection table a 100% inspection with CCD line scan camera and a xy moveable optical microscope is installed, as seen in Figure 4.

Figure 4: Roll-to-Roll optical inspection system encased in a clean room carbine ISO6 to minimize particle contamination during inspection process.

Potential and challenges for the different kind of flexible substrates

Different kind of flexible substrates for roll-to-roll processing have in particular their advantages and disadvantages regarding, barrier properties, surface quality and web handling. In Table 1 summarize the substrate properties which have been evaluated for roll-to-roll OLED fabrication.

Table 1: Comparison of different kind of substrates which have been evaluation for roll-to-roll OLED fabrication.

	Metal foils	**ultra-thin glass**	**Polymer films**
Bendability	o	O	√
permeation barrier	√	√	o
roll-to-roll process-ability	√	(√)	√
surface roughness	o	√	√
Cost	√	O	o
Advantages	good barrier thermal conductivity	good barrier surface quality transparency	transparency high bendability
Disadvantages	top emission additional treatment of reducing surface roughness	Brittle device separation	Possible damage of barrier layer during TCO coatings thermal stability residual water pin hole issue

Metal foils

- Metal foils are suitable for OLEDs regarding impenetrability to water and oxygen.
- However, top-emitting OLED devices on metal foils have a dominant cavity affect and this result in high angular dependency of the out-coupled light [2]. Therefore, application of highly efficient monochrome light are more suitable and is more challenging for white light illumination.
- Metal foils have an excellent thermal conductivity for heat management in OLED devices driven at higher current for high brightness requirements.
- An extra planarization layer of RMS < 3 nm is needed to achieve stable OLED devices. The leakage current will be influenced mainly by the peak to valley roughness value [3].

Ultra-thin glass

- Roll-to-roll manufacturing on ultra-thin glass (50 – 200 µm) has a perfect barrier properties for OLED devices without pin hole nucleation.
- No further barrier film coatings are needed to reach the required barrier requirements for OLED devices. Especially, flexible glass is suitable for sputtering of highly conductive ITO layers of < 15 Ω and optical transparency > 90 %.
- However for winding of ultra-thin glass much more attention needs to be drawn for the equipment and a big challenge is to guarantee high edge stabilities of the glass without any initial micro cracks over several 100 meters on coils.

Polymer films

- Flexible OLED devices on transparent barrier films have a tendency of better light out-coupling properties because of a comparable refractive indices between the polymer film and organic materials.
- A challenge for flexible barrier film encapsulation is to guarantee sufficient and reproducible barrier properties against water and oxygen over several 100 meters of roll materials. The reproducibility correlates with the film cleanliness and particle contamination during barrier film coating process.
- Plastic barrier films accumulate water in the film and water inclusions in polymer interlayers inside the barrier layer stacks. The introduction of novel storage concepts under air tight conditions must be considered.
- OLED devices on plastic substrates allows robust, highly flexible and simple converting, but pin hole level, sensitivity of barrier film layers and residual water needs to be improved.

Building a bridge for pilot production of flexible OLED devices within the EU PI-Scale project

Within the European funded project PI-SCALE an open access pilot line offering will be established. The target is to offer world class capability in customizable flexible OLED lighting, enabling the latest in flexible OLED lighting innovations to be quickly turned from R&D to mass manufacturing. The pilot line brings together Europe's experts and state-of-the-art infrastructure for flexible OLED fabrication:

Figure 5: Consortium of the European PI-Scale project.

The pilot line provides independent, open access capability in:

- Specialist high performance moisture barrier and electrode films
- Sheet-to-sheet and roll-to-roll flexible OLED lighting fabrication
- Flexible device encapsulation
- Lamination, bonding and system-level hybrid integration of thin film flexible electronics

Our pilot line offers the latest innovations on flexible OLED lighting, bridging the gap between R&D and mass manufacturing.

Conclusions and Outlook

The OLED roll-to-roll fabrication line allows stable OLED devices on metal, plastic barrier film and ultra-thin glass substrates. At present 15 m roll-to-roll OLED coating campaigns are in focus to evaluate the OLED device behavior on different kind of substrates. A 15 m roll of working OLED devices on PET barrier film have been demonstrated, as seen in Figure 6 within the European PI-Scale project.

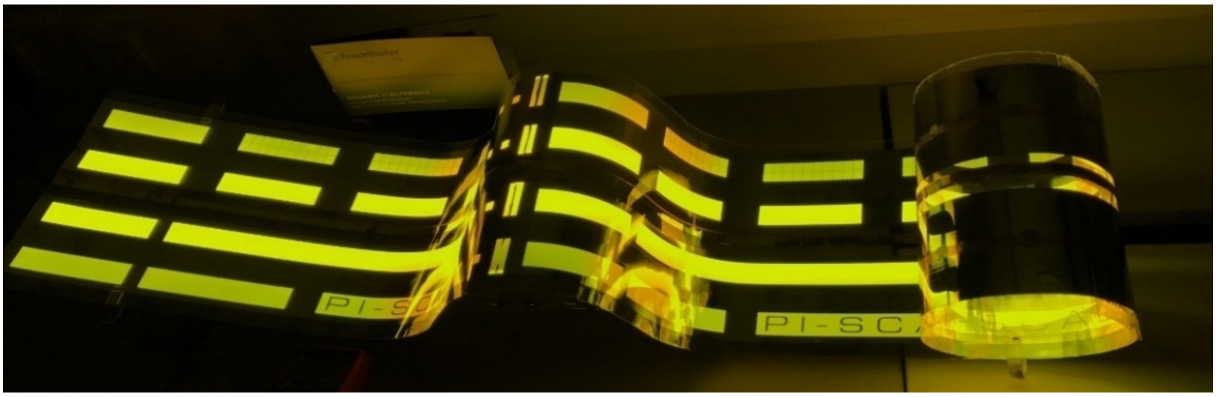

Figure 6: The photograph shows 100 x 100 mm² working OLED devices on a several meter long and 300 mm wide OLED demonstrator on 50 µm ultra-thin glass.

For the future work a several developments and evaluations are in focus:

- Minimization of the substrate damage during the winding process to minimize the leakage current and in particular for plastic barrier films no damage of the ultra-high barrier properties.
- An efficient roll-to-roll drying process or dry storage concepts for roll materials is essential to allow the introduction of roll-to-roll OLED production.
- Damage of barrier film layers during TCO coating needs to be further understood and optimized. Ultra-thin glass could be a promising alternative to plastic barrier film to maintain the ultra-high barrier properties after several windings.
- Improvements of the planarization layers on metal foils and damage free back side of

the web.

- Laser cutting of ultra-thin glass laminates in different material combination with edge stabilities of at least 300 MPa (goal 500 MPa).
- Stable and reliable electrical contacts with low contact resistance on flexible substrates.

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