Triple-Nozzle Revolving Evaporation Source for RGB Direct Patterning OLEDoS Mass Production

Sungmoon Kim*, Daejoon Chi*, Jonghun Jeon*

***R&D Center of Depolab Inc., Gyeonggi-do, Korea**

Abstract

Triple nozzle can concentrate deposition materials within ±10° deposition angle region and can make under 0.3μm mask shadow. We have developed the triple nozzle revolving source that arrange multiple triple nozzles with appropriate 2-dimensional layout on plane source. And, by rotating the source during deposition, it can make good film thickness uniformity and good mixing homogeneity. Also, it can achieve material utilization about 30% and long continuous operation time over 200hrs because the collimator that block low angle particles is not needed. We expect that this technology will make a significant contribution to the mass production of RGB pattern OLEDoS.

Author Keywords

AMOLED; AR/VR; Collimated flux; Ultra-high resolution; Material utilization

1. Background

As the industries utilizing virtual reality continue to develop, the demand for micro-displays is increasing. Among them, OLEDoS is being widely adopted in many devices due to its high brightness and low power consumption. Currently, most OLEDoS in use is White OLED device based on tandem structures and color filters. In contrast, the RGB pattern OLEDoS, which forms individual RGB emission layers using precise masks, achieves three times higher power efficiency compared to White OLED devices and significantly reduces heat generation during device operation. High power efficiency greatly contributes to extending the usable time of VR devices, which inherently rely on batteries, with a single charge. Moreover, reducing the heat generated during device operation is critical, as excessive heat can cause discomfort, particularly for VR devices used in close proximity to the human eyes. For these reasons, many companies are striving to achieve mass production of RGB pattern OLEDoS.

To fabricate RGB pattern OLEDoS panels, ultra-high-resolution pixel deposition processes are required. In AMOLED pixel forming process, the linear evaporation source is used in general. The linear evaporation source has nozzle array that evaporation particles pass through. The flux of particles emitted from each nozzle forms cosine to the nth shape angular distribution. The n value of conventional linear source is 2~3. It is very difficult to make high n (collimated flux) source because of entropy law. The low angle (under 60 degrees from horizontal line) flux are about 60% of emitted particles. It can cause several technical issues such as mask shadow effect, nozzle clogging issue and material waste problem. At first, mask shadow effect is that pattern boundaries are blurred by low angle deposition particles digging into the gap between fine metal mask and substrates. Also, low angle particles mostly don't fly to the substrates and deposit on shield or angle limit plate or other parts nearby nozzles. As the operation time goes by, the deposition material grows thicker and finally nozzle clogging can be occurred. This is important issue to prevent increasing continuous operation time in AMOLED mass production. At last, the low angle flux is deposited on shield and waste. It is hardly recycled because it is contaminated with other deposition material. So, material utilization of conventional linear source is under 30%. It is importance issue in OLED industry because cost reduction is key issue for OLED market expansion.

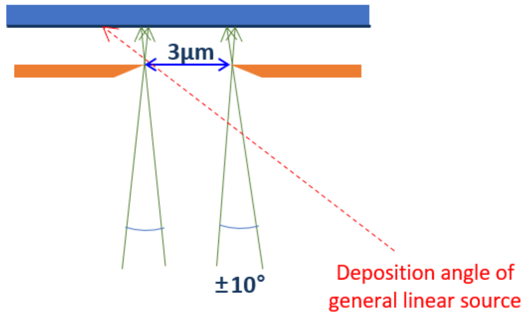

Figure 1. Deposition angle region for 3,000ppi RGB pattern micro OLEDoS device

Also, since the size of displays used in VR/AR devices is approximately 1 inch, achieving a resolution higher than FHD on such micro-displays requires a pixel density of at least 3,000ppi. To realize this, the size of each pixel must be as small as about 3μm. For this, a reliable high-precision mask must first be prepared. However, even if a precise mask shadow is available, the development of an evaporation source capable of minimizing mask shadowing must also be undertaken. To implement pixels of 3μm size with 1μm spacing between them, the mask shadow must be reduced to a level of 0.2–0.3μm. For this, an evaporation source is needed that can emit collimated flux, ensuring that all deposition flux is concentrated within a deposition angle range of ±10° on the substrate.

2. Deposition Methods for RGB OLEDoS

To fabricate 3,000ppi RGB pattern OLEDoS panels, a deposition method capable of concentrating the deposition flux within a deposition angle of ±10° is required. There are two main approaches commonly applied to achieve this. The first method involves attaching a collimator above the linear evaporation source to block flux emitted at angles bigger than ±10°. This allows only flux at higher angles to be deposited. However, this approach has significant limitations. As operation time goes by, most of the emitted materials has been deposited on the collimator, increasing the thickness of the material growth. This makes continuous long-term use infeasible, requiring periodic replacement and cleaning of the collimator. Additionally, as most of the emitted materials are deposited on the collimator, material utilization drops to around 1%. Furthermore, when using a linear evaporation source, a scanning motion of the evaporation source is necessary. This motion can generate vibrations and particles, potentially causing misalignment of the mask and defects in pixel formation.

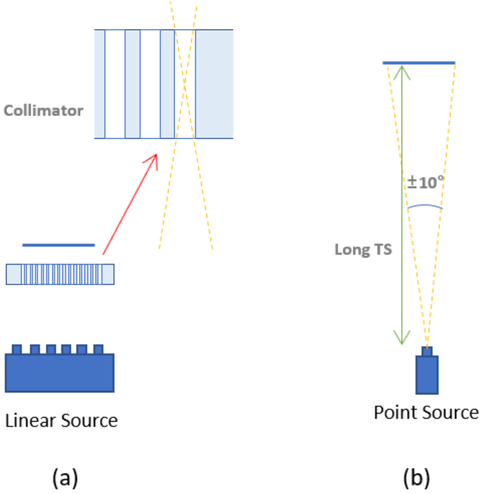

Figure 2. Deposition methods for RGB pattern OLEDoS (a) Linear source with collimator (b) Long TS point source

The second method involves placing a point evaporation source as far away as possible from the substrate to ensure that the OLEDoS substrate falls within the ±10° flux region. Typically, OLEDoS device utilize 12-inch wafers, requiring the point evaporation source to be positioned at least 1500 mm away from the substrate. However, this approach has its drawbacks. Similar to the linear evaporation source, the material utilization efficiency is less than 1%, and the continuous operation time of the point evaporation source is short. Additionally, the large distance between the substrate and the evaporation source increases the size of the deposition chamber and the height at which the substrate must be moved.

These technical issues, such as low material utilization efficiency and short continuous operation time pose significant obstacles to the mass production of RGB pattern OLEDoS panels. To overcome these limitations and ensure extended continuous operation while improving material utilization efficiency, it is essential to develop an evaporation source capable of concentrating the emitted flux within a deposition angle of ±10° directly.

3. Introduction of Triple Nozzle Evaporator

We had developed and announced Collimating and Recycling Source (CnR Source) that can make collimating flux (high n flux) and can recycle materials not used for making thin film on substrates. The CnR source has unique nozzle structure and recycling path. The principle of CnR source is as follows. Firstly, the evaporation particles are emitted from initial nozzle. Among those particles, the low angle particles are leaded down along the recycling path and condensed on the inner surface of recycling basket. And other high angle particles pass through final nozzle and finally make collimated high n flux. As a result of angular flux distribution measurement of CnR Source, the n value is maximum 12 where the n value of general source is 3.

Although the flux of CnR source is more collimated than general source, it is difficult to make higher n value flux than 12. It is not enough for ultra-high resolution such as 3,000ppi. So, we added one more nozzle structure at CnR source and make triple nozzle evaporator. Figure 3 is a conceptual picture of triple nozzle evaporator and comparison between single nozzle and dual nozzle and triple nozzle structure.

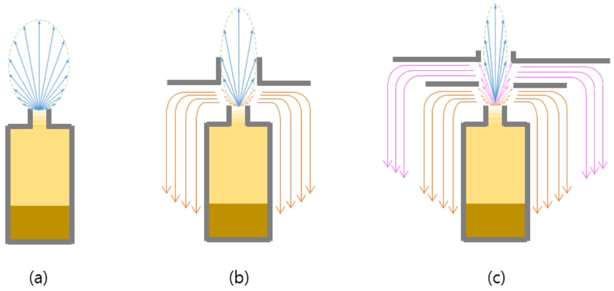

Figure 3. Concept design of triple nozzle CnR source. (a) single nozzle source. (b) dual nozzle CnR source. (c) triple nozzle CnR source

As you can see in the picture, triple nozzle evaporator has one more nozzle structure above dual nozzle CnR source and has one more recycling path separated with first recycling path. We expected that additional nozzle and recycling path can make inner pressure below final nozzle become lower than dual nozzle source. As inner pressure became lower, the collision probability between evaporation molecules decreases. And then, we can make more collimated flux because low angle flux is mostly created by collision between particles.

Based on the concept design, we made triple nozzle source. It is composed of triple nozzle, crucible, recycling paths, recycling basket and heater. We optimize heat-up condition for preventing material clogging at nozzle and recycling path. On the other hand, we keep the recycling basket at low temperatures. When evaporation molecules reach at the surface of recycling basket, molecules would condense at surface because of low temperature. It can generate pressure difference between top and bottom of recycling path. And it is helpful to keep continuous recycling flow. We perform the angular flux distribution measurement about single nozzle evaporator (general point source), dual nozzle evaporator and triple nozzle evaporator. The results of angular flux distribution are illustrated in Figure 4. As you can see in this graph, the 90% angle region of single nozzle is ±55°, and dual nozzle is ±28°, and triple nozzle is ±10°. In triple nozzle evaporator case, 90% amount of total flux are concentrated within only ±10° region. It is expected that the collimated flux of triple nozzle source would be good performance for ultra high resolution OLED.

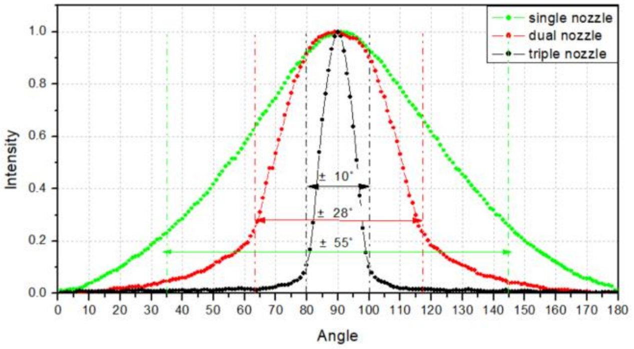

Figure 4. Angular flux distributions and 90% concentrated region of single nozzle, dual nozzle and triple nozzle evaporator

Triple nozzle source can gather the low angle flux in recycling basket. The recycling ratio of triple nozzle evaporator is 82% because over most of low angle flux are leaded down to recycling basket. However, gathered material in recycling basket is high purity 99.99%. So, we can re-use gathered material by itself.

4. Triple Nozzle Revolving Evaporation Source

We have developed a triple nozzle capable of emitting collimated flux, with over 90% of the flux concentrated within a deposition angle range of ±10°. Since the triple nozzle operates as a point evaporation source, it is necessary to design an evaporation source and deposition method that can utilize these nozzles to create thin films with uniform thickness distribution across a 12-inch wafer. The conventional deposition method commonly is the linear evaporation source that involves aligning nozzles linearly and scanning under substrates during deposition. However, applying triple nozzles with collimated flux into the linear source introduces new challenges. OLED devices consist of multi-layered organic thin films, where each thin film typically requires deposition of a mixed layer of two materials, such as Host and Dopant. To achieve uniform mixing ratios, referred to as "mixing homogeneity," is critical for performance. Poor mixing homogeneity can degrade the brightness and lifetime of OLED devices. Since the triple nozzle emits collimated flux concentrated within ±10°, the mixing homogeneity significantly decreases, dropping to below 6%, as shown in the figure 5. Mixing homogeneity is calculated as the size of the intersection of fluxes divided by the size of their union. This poor homogeneity makes it difficult to apply the triple nozzle into a linear evaporation source. Additionally, as previously mentioned, the scanning motion of linear evaporation sources introduces vibrations and particles, which pose further challenges for mask alignment and thin-film formation of high resolution RGB pattern OLEDoS.

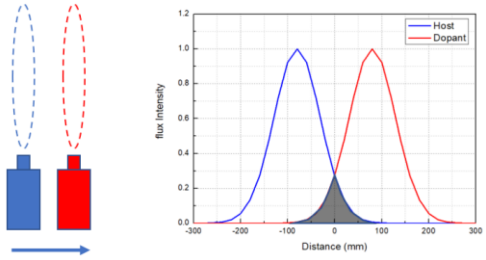

Figure 5. Mixing homogeneity of linear source that applied triple nozzle.

We have developed a new deposition method to overcome these shortcomings while achieving uniform thin-film thickness and good homogeneous mixed films, all while utilizing triple nozzles. In this method, an evaporation source with multiple triple nozzles are arranged at plane source below the substrate. The evaporation source is divided into two sections, one for Host and the other for Dopant, and triple nozzles are arranged in a two-dimensional layout on each section's plane. The nozzle arrangement is designed such that the number of nozzles increases as the distance from the substrate's center increases. During deposition, the evaporation source rotates. Since the number of triple nozzles increases toward the outward, rotating the source ensures a uniform deposition thickness distribution. Additionally, by rotating both the Host and Dopant evaporation sources together at an appropriate speed, highly homogeneous mixed films can also be achieved. This approach is similar to the method used in many R&D deposition systems for small substrates, where the substrate rotates. However, in this case, the evaporation source rotates instead. We refer to this deposition method as triple-nozzle revolving evaporation source. By employing this method, it is possible to use triple nozzles to emit collimated flux while achieving uniform thin-film thickness and improved homogeneity in mixed films. Furthermore, compared to linear motion systems, rotational motion systems have the advantage of using ferrofluid seals, which produce less vibration and fewer particles.

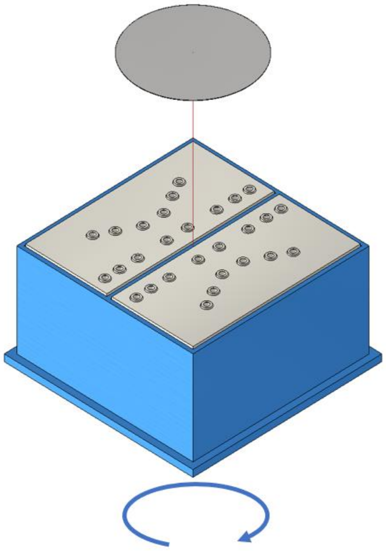

Figure 6. Triple Nozzle Revolving Evaporation Source

5. Film Thickness Profile of Triple Nozzle Revolving Source

The triple-nozzle revolving source is composed of multiple triple nozzles arranged on a flat plane. The arrangement of the nozzles follows a specific pattern. As shown in the figure 6, the nozzles are placed in such a way that two triple nozzles are positioned on the circumference of the first circle drawn from the rotation center. On the second to fourth circles, four triple nozzles are placed on each circumference. Additionally, the diameters of the circles decrease gradually as they move outward. The flux emitted from these arranged triple nozzles is shown in the figure 7. When the source rotates, a uniform circular flux distribution, as depicted in the figure 8, is created. The deposition thickness uniformity of the rotating triple-nozzle source, as measured, was found to be 0.73% across the substrate area, as shown in the figure 8.

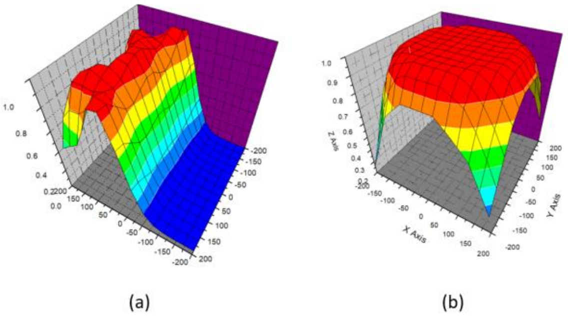

Figure 7. Thickness profile of triple nozzle revolving source (a) before rotation and (b) after rotation

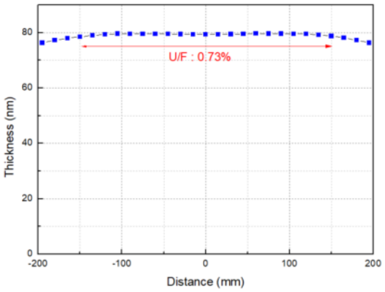

Figure 8. Thickness uniformity of triple nozzle revolving source

The triple-nozzle revolving source has a short distance of 500 mm from the substrate and does not use flux-blocking equipment such as collimators, which results in higher material utilization efficiency compared to other deposition methods. The figure 9 shows the two-dimensional deposition distribution of the triple-nozzle rotating source, indicating that the material utilization efficiency, which refers to the amount of material directed toward the 12inch substrate, is high at 28.5%.

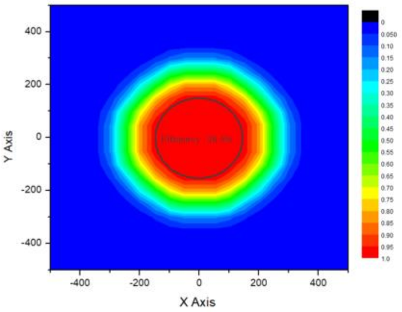

Figure 9. 2-dimensional flux distribution and material efficiency of triple nozzle revolving source

6. Mask Shadow of Triple Nozzle Revolving Source

The triple nozzle revolving source that utilize triple nozzles can concentrate over 90% of the emitted flux within a deposition angle of ±10º, as mentioned before. This collimated flux can minimize the mask shadow. The region where the pixel thickness increases from the starting point to the maximum thickness is referred to as the mask shadow. Geometrically, when the gap between the substrate and the mask is 1µm and deposition is carried out within a ±10º deposition angle region, the mask shadow can reach a maximum of 0.35µm. To measure the actual mask shadow, a mask shadow measurement jig was prepared and testing was conducted. Conducting tests with an real mask is challenging due to difficulties in obtaining ultra-high-resolution masks and high-precision aligners, as well as the difficulty in measurement. Therefore, in this study, the mask shadow evaluation was performed using a mask jig that magnified the mask 1,000 times. The pixel width of the mask jig was 3 mm, and the distance between the substrate and the mask was 1 mm.

According to the evaluation results in Figure 10, the distance from 10% to 90% of the mask shadow length is 2.6 mm, which corresponds to 2.6µm when applied to the actual mask. The slope of the mask shadow gradient is indicated by the blue line, with a gradient angle of 7.4°. This angle can be considered as the average value of the triple nozzle angle distribution.

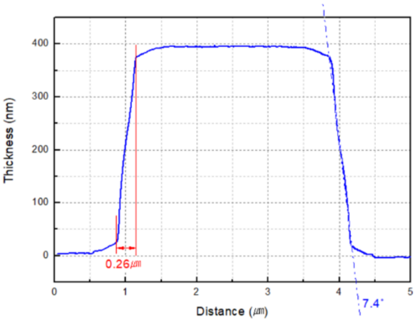

Figure 10. Thickness profile and mask shadow of pixel fabricated by triple nozzle revolving source

Additionally, there are some tail regions around the minimum and maximum thickness, which can be attributed to the low-angle flux emitted at less than 10% from the triple nozzle and collisions occurring in the space above the nozzle.

7. Impact

As explained above, by utilizing a triple nozzle revolving source, it is possible to concentrate over 90% of the emitted flux within a ±10° angle region. By appropriately arranging the triple nozzles in a two-dimensional plane and rotating them during deposition, a triple nozzle revolving source can deposit thin films on a 12-inch substrate with a good thickness uniformity of less than 1%. Since it creates a circular deposition flux, the material utilization efficiency can be increased to about 28%. Additionally, by simultaneously rotating both the host evaporation source and the dopant evaporation source, a well-homogenized mixed thin film can be obtained. Since there is no need for a flux blocking equipment to block low angle deposition materials, such as a collimator, and the material utilization efficiency is high, continuous use for over 200 hours is possible.

Using this triple nozzle revolving source offers the following advantages. The triple nozzle revolving source concentrate the deposition material with a deposition angle within ±10°, reducing the mask shadow to less than 0.3µm. This makes the mass production of ultra-high-resolution RGB pattern OLEDoS with over 3000ppi possible. Additionally, since the distance to the substrate is less than 500 mm and a collimator is not required, a circular flux similar shape with the substrate can be created, increasing material utilization efficiency to about 30%. This improvement enhances the cost competitiveness of OLEDoS. The low-angle material gathered in the recycling basket has a purity of over 99.9%, making it immediately recyclable without further purifying processes. Furthermore, since periodic cleaning is not necessary, the continuous operation time can be extended to over 200 hours. Also, even if the substrate size is increased, if additional triple nozzles are placed in the plane, the mask shadow can be maintained at the same level. It can make advantageous for scaling up the substrate size.

8. Reference

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