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A Magnetic Metal Hard Mask on Silicon Substrate for Direct Patterning Ultra-High-Resolution OLED Displays

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Abstract: With the development of virtual reality/augmented reality (VR/AR) display devices, the conventional fine metal mask is limited by the wet etch process, which no longer meets the demand for high pixels per inch (PPI) displays. We deposited a layer of magnetic metal on the silicon substrate by physical vapor deposition (PVD), and then developed a 2-inch, 3175 PPI magnetic metal hard mask on silicon substrate (MMS) through deep silicon etching and other micro-nano processing for patterning Organic Light-Emitting Diodes (OLED) displays, which can achieve smaller pixel size and higher PPI. MMS can not only solve the bottleneck problem of the traditional invar alloy shadow mask with low PPI, but also reduce the bending caused by the deformation of the silicon-based mask due to gravity, so that it achieves high PPI and higher uniformity in OLED displays.

Keywords: shadow mask; magnetic metal hard mask on silicon substrate; high PPI; high uniform pattern; OLED displays

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1. Introduction

As consumers and the industrial and military markets move towards AR and VR applications, there is a pressing need for high resolution near-eye devices. To achieve a truly immersive experience, VR devices should at least have a pixel density of 2000 PPI to eliminate the screen door effect [1]. The evaporation size of organic light-emitting materials has become smaller and smaller in order to meet the demand for increasing resolution. Patterning of small-scale organic materials is a crucial step in the fabrication of VR devices.

Photolithography is usually not capable of patterning organic materials since the solvent used in the process may degrade the materials to be patterned. The conventional fine metal mask (FMM) such as Invar alloy mask is commonly used in the OLED display industry, as shown in Figure 1a [2]. Due to the limitations of the wet etching process with a pixel size of approximately 30 μm [3], as illustrated in Figure 1b, it is difficult to meet the pixel size $\leq$10 μm required by the high PPI AR/VR micro-display industry [1], as shown in Figure 1c. To overcome the limitations of the FMM technology, many processes have been proposed. Ink-jet printing [4–7] has been used but it suffers from potential drawbacks such as low throughput and non-uniform thickness. Other alternative patterning methods demonstrated include laser-induced thermal imaging [8,9] and laser-induced sublimation transfer [10,11]. With laser-induced thermal imaging, sharp edge patterns are difficult to achieve for polymer layers, and laser-induced sublimation can only be used to pattern small molecules [12].

In this paper, we have developed a silicon-based fine mask that can achieve high PPI and uniform evaporation. However, under the conditions of the influence of gravity; the bending of the silicon-based mask will affect the sizes of the vapor deposition pattern in different regions. We introduced a magnetic metal film in a new process, which not only acts as the etching barrier layer of the silicon substrate but can also use the upward

magnetic force provided by the evaporation equipment to balance the hollow area bending of the silicon mask plate due to gravity.

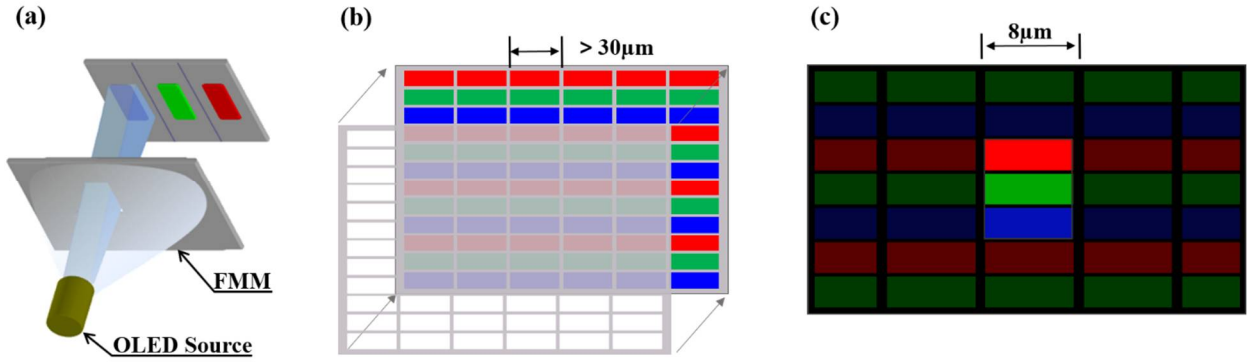


Figure 1. (**a**) Schematic diagram of OLED evaporation, (**b**) traditional OLED displays, (**c**) target OLED display.

2. Materials and Methods

The 2-inch MMS was fabricated on 4-inch Si wafer, as shown in Figure 2. The area of the free-standing magnetic metal hard mask on silicon substrate structure is 40 mm × 40 mm. The vertical thickness is approximately 20 μm, and pixel size is 4 μm × 4 μm.

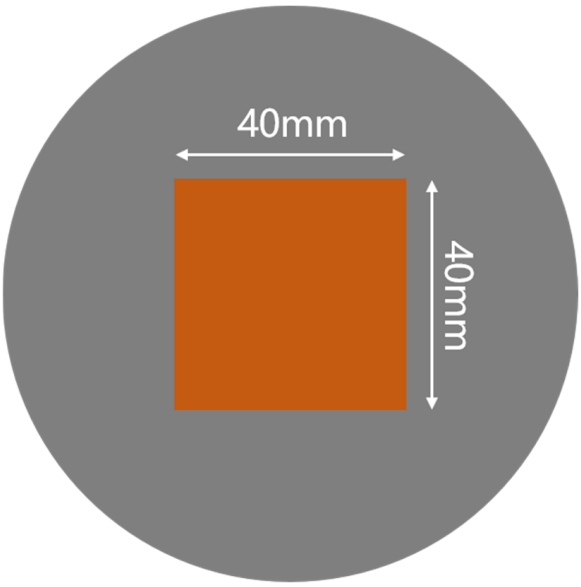


Figure 2. MMS dimensions.

The process flow of MMS fabrication is illustrated in Figure 3. First, a layer of low-stress silicon nitride (SiN_x) was deposited on both sides of the wafer by low pressure chemical vapor deposition (LPCVD) and then a Ni layer was deposited by Sputter or Ebeam at the front side. Photolithography and inductively coupled plasma etching (ICP) were first performed on the front side of the wafer to create an aperture array in the Ni layer. Photolithography and reactive ion etching (RIE) were acted on the backside of SiN_x layer to define the boundary of the free-standing area. After the front side protected by 200 nm SiO_2 layer, 200 nm SiN_x and black wax, the exposed silicon on the backside was etched by 30% KOH solution at 70 degrees centigrade until left with 20 μm thick Si. Next, after the black wax was removed with $CHCl_3$, the SiN_x/SiO_2 protective layer on the front side and the low-stress SiN_x not covered by Ni were etched with RIE. At the last step, the remaining 20 μm thick Si was etched with ICP, according to the shape of Ni with deep silicon etching process.

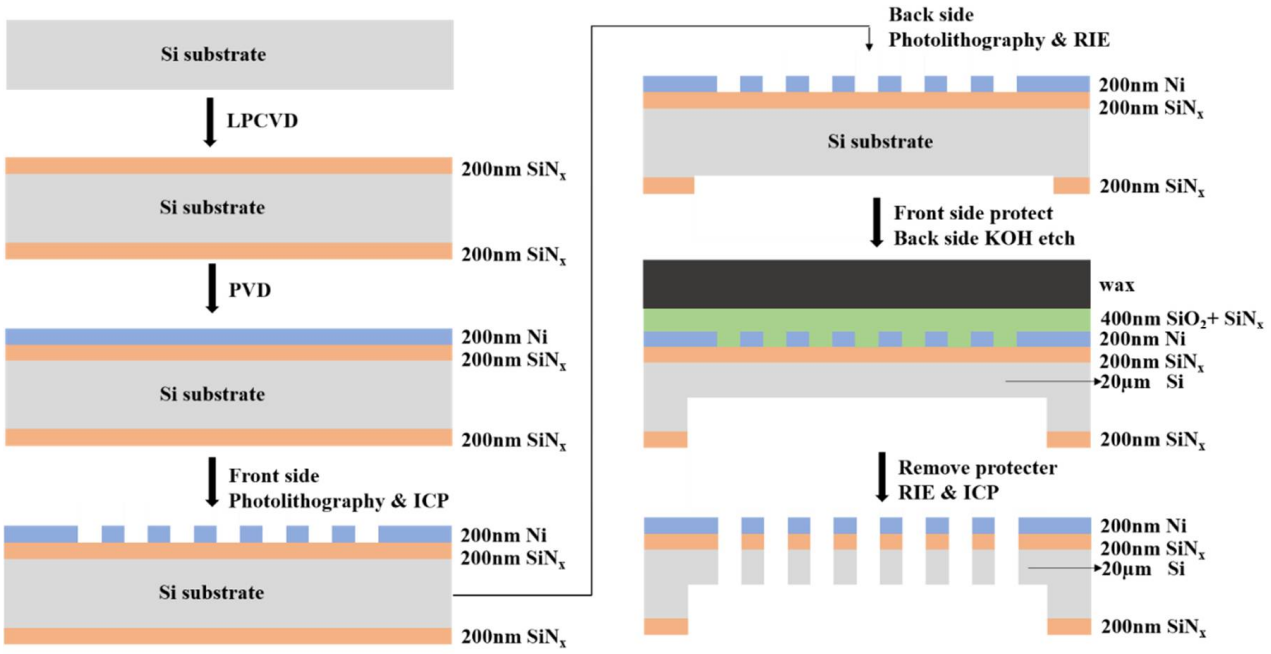


Figure 3. MMS process flow.

The working mechanism of the evaporation mask is illustrated in Figure 4. The robotic arm transfers the substrate to the position to accurately align with the mask underneath. The contact plate above the substrate moves downward to compress the substrate and fix it. Meanwhile, the magnetic field to make the mask and the substrate fit more closely. As the thermistor heats the crucible below, the organic light-emitting material is evaporated and patterned on the surface of the inverted substrate.

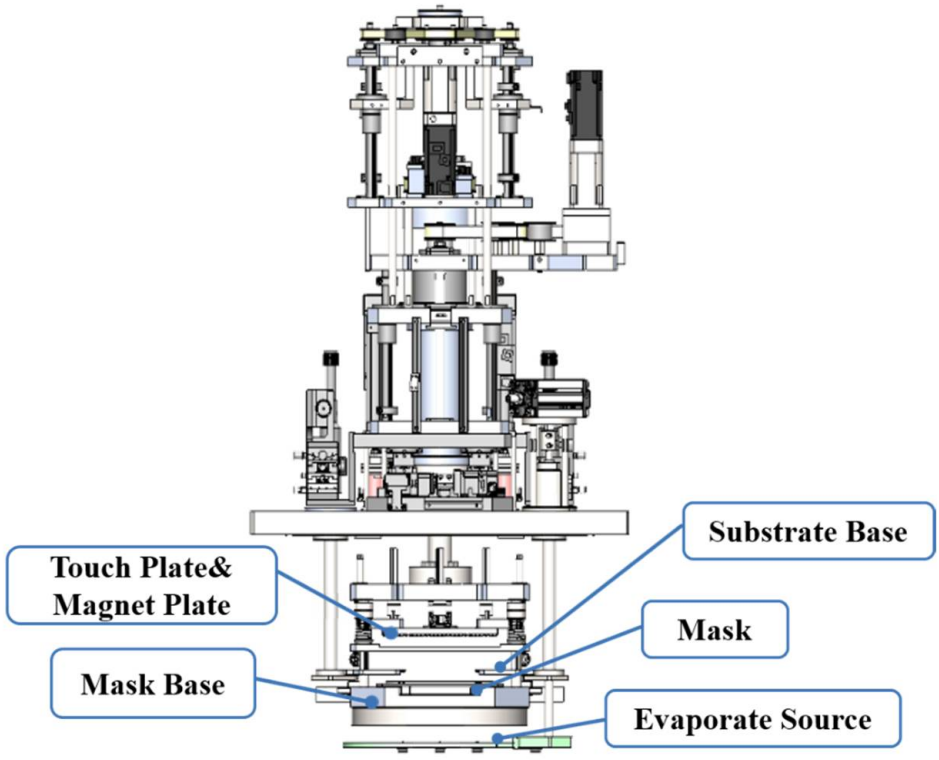


Figure 4. Working mechanism of evaporation mask.

3. Results and Discussion

3.1. Measures to Improve PPI

VR/AR products have an increasing demand for high PPI OLED displays. However, conventional fine metal masks such as the Invar alloy mask cannot further reduce the pixel size to less than 30 μm due to the limitation of the wet etching process accuracy. To solve this problem, we innovatively use silicon-based materials and the hard mask manufacturing process, which successfully promote the pixel size to less than 10 μm. However, there is a problem that the size of evaporated pattern differs between mask center and edge.

Taking the most common point evaporation source system as an example, a 10 μm~20 μm gap (Δh) is often set between the mask and the substrate to avoid particle contamination caused by contact. The exist of Δh will cause the size of actual evaporation pattern (pattern A + pattern B) to be larger than the mask design value (pattern A), which is called the shadow effect [13], as shown in Figure 5. As the Δh increases, the pattern B (Δs) increases, and the shadow effect becomes more obvious. The silicon-based hard mask will bend downwards under the influence of gravity, making the gaps different from mask center to edge, and the Δs will change accordingly. Eventually, the CDs of organic light-emitting material evaporation pattern are nonuniform, resulting in an uneven display of the device.

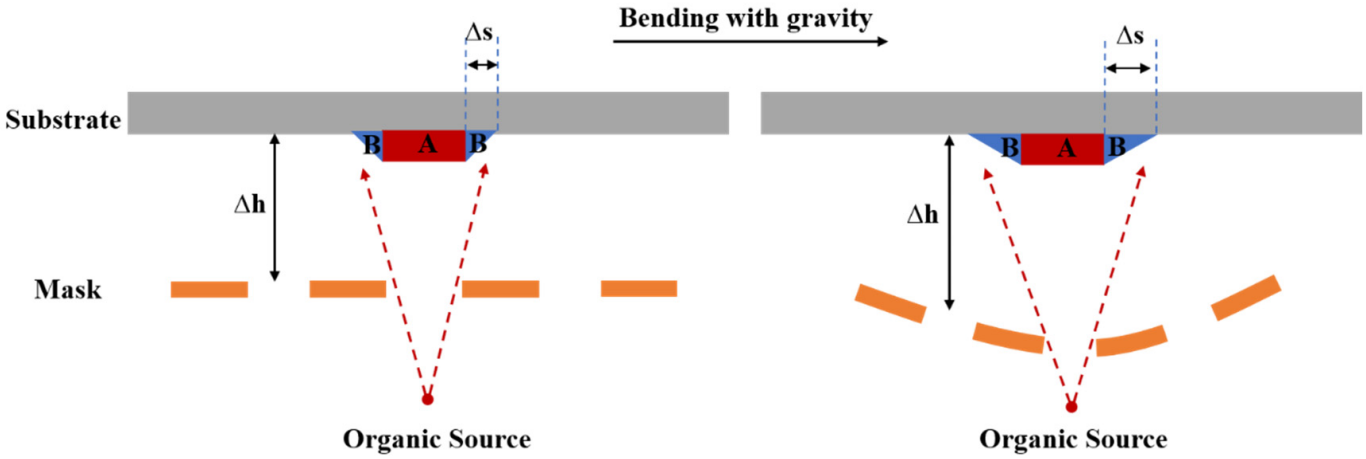


Figure 5. Diagram of shadow effects (ΔS) with different gaps (Δh).

3.2. Measures to Improve Uniformity

The introduction of magnetic metal film solves this problem, which not only acts as the etching barrier layer of the silicon substrate in the deep silicon etching, but also provides upward magnetic force to balance gravity. In addition, considering the strength of the mask structure and the plugging rate of the through holes, the vertical thickness of suspended part in silicon-based hard mask is approximately 20 μm. We use finite element analysis to carry out simulation experiments. Under the condition of the influence of gravity and fixed constraints, the bending of the silicon-based mask(Δh) is 11.9 μm in Figure 6a–c. Furthermore, we introduced a magnetic metal film in new process, and the magnetic metal hard mask on silicon substrate has smaller bending (Δh = 2.97 μm). As the difference of gaps (Δh) from mask center to the edge gets shorter, the sizes of pattern B (Δs) get smaller, and the pattern sizes are more uniform, as shown in Figure 6d–f. Figure 7 is the SEM image of a magnetic metal hard mask on silicon substrate. In order to achieve the purpose of repeated or long-term use, MMS can be cleaned with ultrasonic vibration in organic solvent.

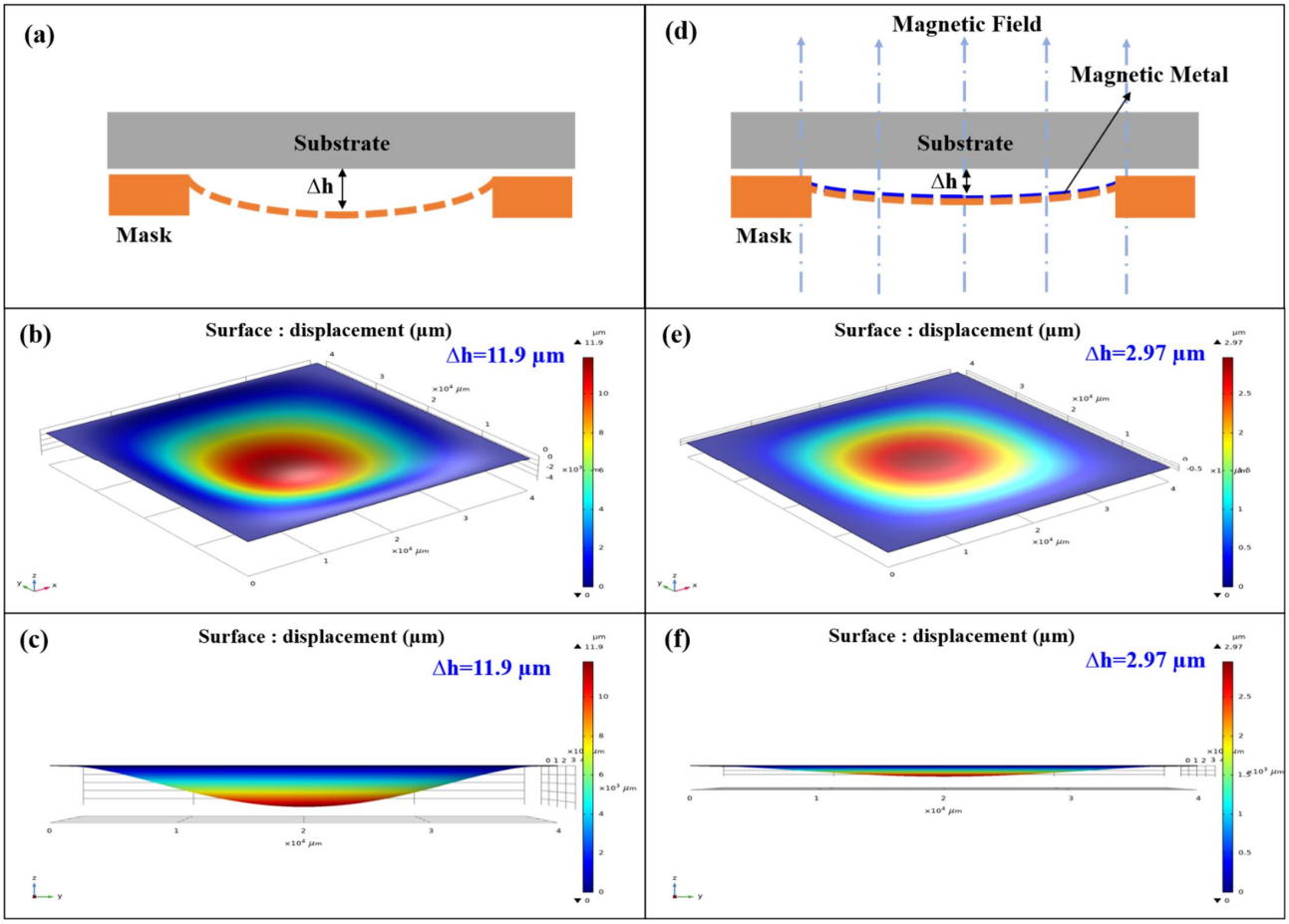


Figure 6. (**a**) Cross section schematic of Si based mask. (**b**,**c**) Simulated result of bending is 11.9 μm. (**d**) Cross section schematic of MMS. (**e**,**f**) Simulated result of bending reduces to 2.97 μm.

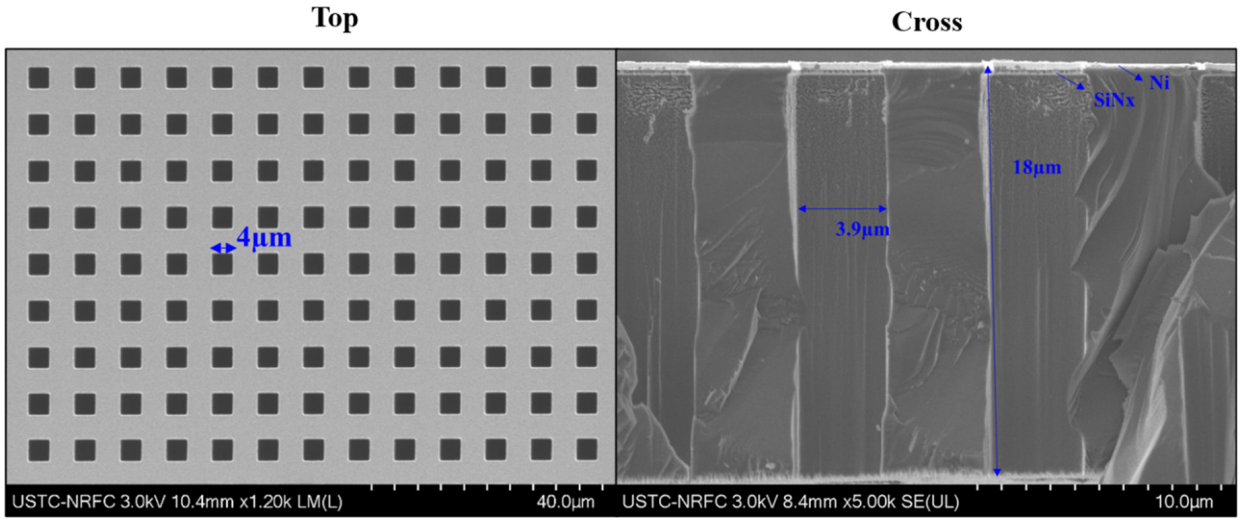


Figure 7. The SEM image of MMS.

4. Conclusions

We have innovatively developed a 2-inch, 3175 PPI magnetic metal hard mask on a silicon substrate in order to meet the demand for high PPI and high uniformity of the micro-display in the VR/AR field. Thereinto, the silicon-based hard mask realizes high PPI, and the magnetic film layer which not only acts as the etching barrier layer of the

silicon substrate, but also provides upward magnetic force to balance gravity realizes high uniformity display.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vieri, C.; Lee, G.; Balram, N. An 18 megapixel 4.3′ 1443 ppi 120 Hz OLED display for wide field of view high acuity head mounted displays. *J. Soc. Inf. Disp.* **2018**, *26*, 314–324. [CrossRef]
2. Korea IT News. Available online: https://english.etnews.com/20210817200001 (accessed on 17 August 2021).
3. Ghosh, A.; Donoghue, E.P.; Khayrullin, I. Directly Patterened 2645 PPI Full Color OLED Microdisplay for Head Mounted Wearables. *SID Symp. Dig. Tech. Pap.* **2016**, *47*, 837–840. [CrossRef]
4. Hebner, T.R.; Wu, C.C.; Marcy, D. Ink-jet printing of doped polymers for organic light emitting devices. *Appl. Phys. Lett.* **1998**, *72*, 519. [CrossRef]
5. Shimoda, T.; Morii, K.; Seki, S. Inkjet Printing of Light-Emitting Polymer Displays. *MRS Bull.* **2003**, *28*, 821–827. [CrossRef]
6. Carter, J.; Lyon, P.; Creighton, C. Developing a Scalable and Adaptable Ink Jet Printing Process for OLED Displays. *SID Symp. Dig. Tech. Pap.* **2012**, *26*, 523–525. [CrossRef]
7. Lee, D.; Chung, J.K.; Rhee, J.S. Ink Jet Printed Full Color Polymer LED Displays. *SID Symp. Dig. Tech. Pap.* **2012**, *36*, 527–529. [CrossRef]
8. Lee, S.T.; Chin, B.D.; Kim, M.H. A Novel Patterning Method for Full-Color Organic Light-Emitting Devices: Laser Induced Thermal Imaging (LITI). *SID Symp. Dig. Tech. Pap.* **2004**, *35*, 1008–1011. [CrossRef]
9. Lee, S.T.; Suh, M.C.; Kang, T.M. LITI (Laser Induced Thermal Imaging) Technology for High-Resolution and Large-Sized AMOLED. *SID Symp. Dig. Tech. Pap.* **2007**, *38*, 1588–1591. [CrossRef]
10. Boroson, M.; Tutt, L.; Nguyen, K. Non-Contact OLED Color Patterning by Radiation-Induced Sublimation Transfer (RIST). *SID Symp. Dig. Tech. Pap.* **2005**, *36*, 972–975. [CrossRef]
11. Hirano, T.; Matsuo, K.; Kohinata, K. Novel Laser Transfer Technology for Manufacturing Large-Sized OLED Displays. *SID Symp. Dig. Tech. Pap.* **2012**, *38*, 1592–1595. [CrossRef]
12. Jin, H.; Sturm, J.C. Super-high-resolution transfer printing for full-color OLED display patterning. *J. Soc. Inf. Disp.* **2010**, *18*, 141–145. [CrossRef]
13. Jiang, Y.; Tam, B.; Dong, S. 2-inch, 2,000-ppi Silicon Nitride Mask for Patterning Ultra-High-Resolution OLED Displays. *SID Symp. Dig. Tech. Pap.* **2020**, *51*, 909–912. [CrossRef]