Development of 3,000ppi RGB Direct Patterned OLED Micro-display

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ABSTRACT

We have developed the 3,000ppi FMM using UV laser patterning technology and the RGB side-by-side OLED micro-display using Si-wafer pixel driving circuits. These two key technologies enable us to realize AR devices with ultra-high pixel resolution, high brightness, long lifetime and high color purity.

1 Introduction

Recently, in the field of information and communications technologies (ICT), research on technologies that can lead the 4th industrial revolution is actively being conducted. Virtual Reality/Augmented Reality (VR/AR) technology plays the key role in this field [1-3]. In particular, to increase the user's sense of immersion, a device capable of providing and interacting with multi-sensory stimulation experiences is required. Therefore, the performance of a display panel providing image information should be much better than that of a conventional television or mobile device. OLED micro-display is not a completely different technology from existing OLED mobile phone. However, there are differences in some structural and process respects. First, the pixel size is different. The pixel size of OLED panels used in televisions and mobile phones is between 40 to 200μm, while the pixel size of OLED micro-display is about 3 to 10μm, which is more than 15 times smaller. Therefore, the backplane also uses a glass-based Low Temperature Poly Silicon (LTPS) or oxide TFTs, whereas the OLED micro-display uses a Si-wafer-based CMOS process. OLED micro-display can only be manufactured by top-emission structure. In addition, for lower (anode) electrode, CMOS compatible process should be used, instead of the commonly used Indium-Tin-Oxide (ITO). For wide color gamut, RGB sub-pixels are required: red, green, and blue. Most OLED panels, widely used in smartphones, have a top light emission structure. Red, green, and blue light emitting organic layers of OLED are separately patterned by using FMM, so no color conversion layer (color filter) is required.

On the other hand, in the case of OLED micro-display, the pixel size is so small that it is difficult to elaborately patterning the red, green, and blue light emitting layers with the existing FMM technology. So, most full-color OLED micro-displays use color filters. For OLED TV, white OLED light is emitted toward the glass substrate so called bottom emission, the color filter process does not affect the OLED evaporation because the color filter is located beneath the OLED layers. On the other hand, since the OLED micro-display has a top emission structure, the color filter should be processed on top of the OLED layers.

It is well known that OLED materials are vulnerable to moisture and oxygen, and can be easily damaged by solutions, ultraviolet rays, and high temperatures under color filter patterning process.

Encapsulation and protective layers that can protect the OLED is required. In addition, low temperature special process is required for color filter formation. The color filter process should be carried out at a low temperature of 100 degrees or less. Figure 1 shows the general structure of a full color OLED micro-display.

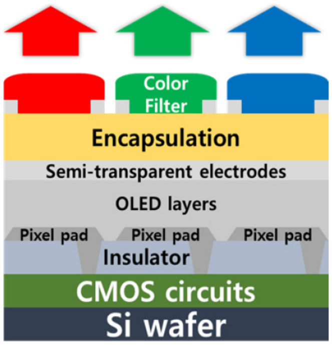


Figure 1. General Structure of White/CF Micro OLED

Some companies like eMagin [4] has recently implemented RGB SBS structure with no color filters by directly patterning the red, green, and blue OLED emitting layers. Since there are no color conversion layers, higher luminance is achieved, and the quantum efficiency is increased. This RGB SBS OLED micro-display can break-through the current bottle-neck low of brightness issue.

2 Laser patterned thin Invar FMM

FMM is conventionally manufactured by wet chemical etching process followed by well-established photo-lithography process. As the resolutions of OLED displays are soaring, the opening size of the FMM should be reduced accordingly. It is challenging to realize the fine pattern because the photo-resist masking pattern suffers under-cut after isotropic wet etching process. To circumvent this fine patterning issues, double-side wet etching process is normally used. But it causes shadow effect at the reverse-tapered region around the hole opening area. (Figure 2(a)) The reverse-tapered region and the non-linear round shaped hole formation affect the thickness uniformity under organic vapor deposition. With wet etching process, it looks like that the 600ppi QHD FMM is the resolution limit because it is very difficult to manufacture the good quality FMM sticks.

On the other hand, the laser patterned FMM can remove the reverse-tapered region because this process does not need double-side patterning. (Figure 2(b)) Spot size of the laser beam can be controlled well below the pixel size and the one side patterning is good enough to make openings of below 10um.

As shown in figure 2, to realize a high-resolution FMM stick, thickness of the FMM foil is another critical factor. To reduce the shadow distance, the Invar foil needs to be thinner. But the rolled invar made by the rolling process causes various problems when its thickness is decreased. This suggests that the current 20um is the thickness limit of the rolled Invar foil. Our approach for thin Invar sheet starts from the thick sheet. By using the TCP (Thickness Control Process), thick Invar foil is slimmed as targeted. TCP processed annealed Invar foil satisfies the thickness variation with less waviness, curling and surface roughness. [5-6]

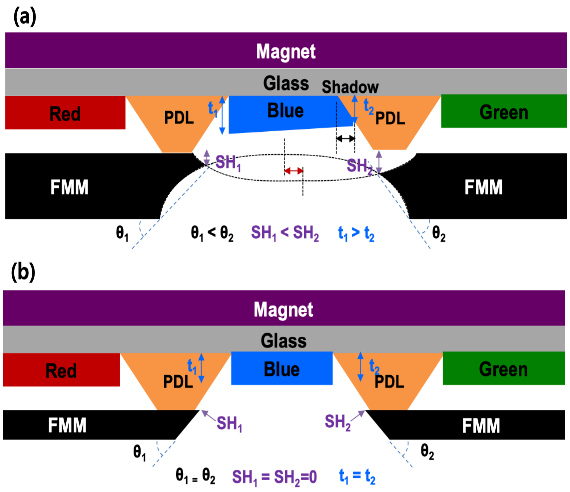


Figure 2. Schematic comparison of the (a) wet etched and (b) the laser patterned FMMs: Shadow distance is depending of the size of step height

3 Characteristics of 1,057ppi FMM

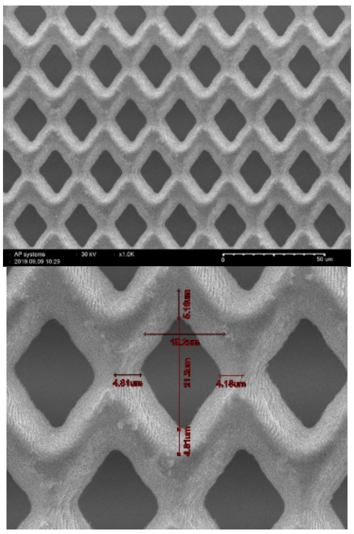


Figure 3. Top view of SEM picture of 1,057ppi FMM

In an intermediate stage to develop 3,000ppi FMM, we fabricated 1,057ppi FMM, first. 1,057ppi FMM has been fabricated for the first time by using thin TCP rolled Invar and laser patterning method as shown Figure 3. Well tapered and sharp rounding patterns can be obtained with the laser patterning process.

Figure 4 shows the optical image and shadow distance of the 100nm thick organic film deposited by using our 1,057ppi FMM. Thanks to very thin Invar thickness of active area and zero step height of Laser patterning process, FMM shows neglectable shadow distance of 0.29µm.

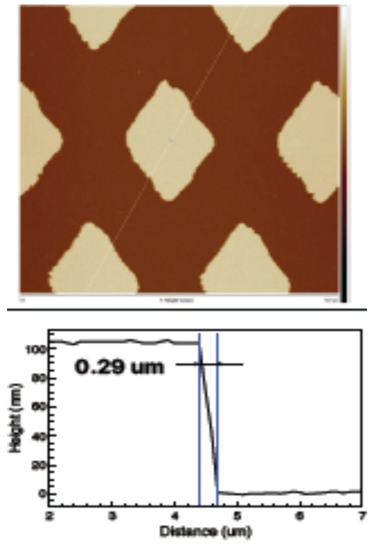


Figure 4. Optical image and shadow distance of deposited organic film using 1,057ppi FMM

With this result, we can expect that if the Invar thickness is thinner, it could be possible to develop ultra-high resolution FMM with 3,000ppi. Using TCP process, we can control the thickness of the FMM active area below 8um.

4 UV Laser System

In order to process an FMM with a resolution of 1,500ppi or higher, it is essential to reduce the laser beam spot size and the IR laser source does not fit our requirements. As shown Figure 5, we need shorter wavelength lasers.

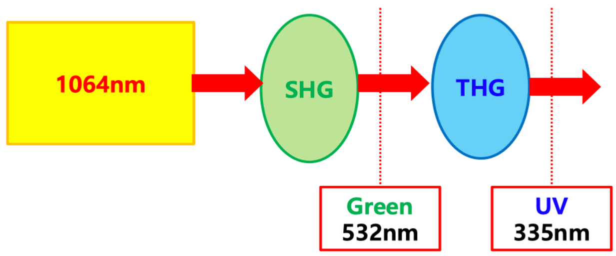


Figure 5. Schematic diagram of UV Laser System

UV Laser is made through optical coupling systems (SHG+THG). Instead of using a separate laser sources, IR laser with basic wavelength of 1064nm is used. SHG is the second harmonic generation and THG is the third harmonic generation. The conventional IR Laser's focused beam size is ~15µm, and the UV laser's is ~2µm. UV laser is our choice for producing 3,000ppi FMM with several um pixels.

5 Fabrication of 3,000ppi FMM

In order to make 3,000ppi FMM, it is necessary to make thin Invar sheet. We make 8um thick Invar film using our TCP process. After that, the active area is process down to 4μm thick using the laser. Finally, ultra-thin active area is processed for pixel holes by UV laser as shown Figure 6.

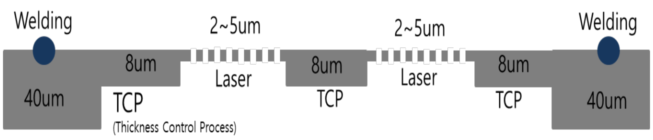


Figure 6. Schematic cross-sectional view of 3,000ppi FMM

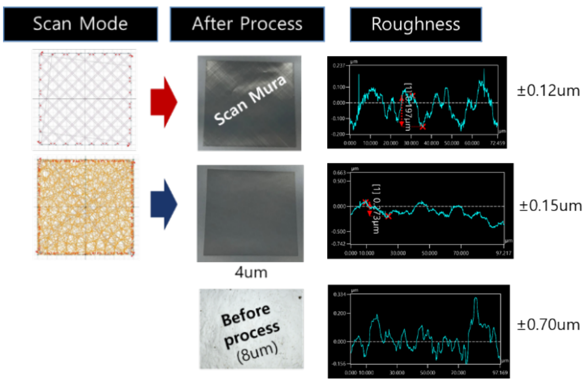


Figure 7. Surface roughness of Laser partial etching with various scan mode

Partial etching was performed using a UV laser to make thinner (From 8um to 4um) the thickness of Invar in the active area before processing a 4um-sized hole. And by unique laser scan mode, the scan-mura of the Invar surface could be significantly reduced, and the surface roughness was 0.12~0.15um as shown Figure 7. It was confirmed that the surface roughness of 8um thick TCP Invar can be reduced by performing a UV Laser partial etching.

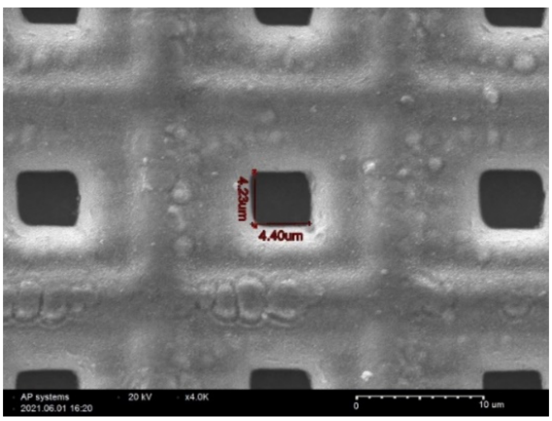


Figure 8. SEM image of vary small size hole in the 4um thick Invar sheet.

A hole of about 4 μm in size was successfully fabricated using a UV laser as shown Figure 8. At this time, the thickness of Invar sheet is 4um. We will use this ultra-high-resolution FMM to fabricate the 3,000ppi RGB SBS Micro OLED display.

To design an RGB SBS pixel, PDL margin between each pixel must be applied. PDL margin is determined by the size of the individual parameters indicated in table1. This PDL margin plays a major role as preventing color mixing by depositing different color organic materials on each RGB pixel.

Table 1. PDL (Pixel Defined Layer) margin by applying multiple factors

	Factor	3,000ppi
FMM	Pixel Position Accuracy	0.3
	Pixel Shape Accuracy	0.3
	Shadow Distance	0.3
Equipment	Align accuracy	0.5
Si BP	Thermal expansion	0.05
	Pattern align accuracy	0.1
	PDL Margin(um)	**2.03**

Furthermore, reducing the PDL margin increases the aperture ratio of the pixel, so the optical efficiency and lifetime of the OLED device can be improved. In particular, the shadow distance is a major factor that can reduce the PDL margin. Therefore, our laser patterned mask is optimum for producing RGB side-by-side OLED micro-display because the step height is negligible. The aperture ratio of the pixel can be increased, and the device lifetime can be increased accordingly.

6 Enhancing efficiency of Micro OLED device

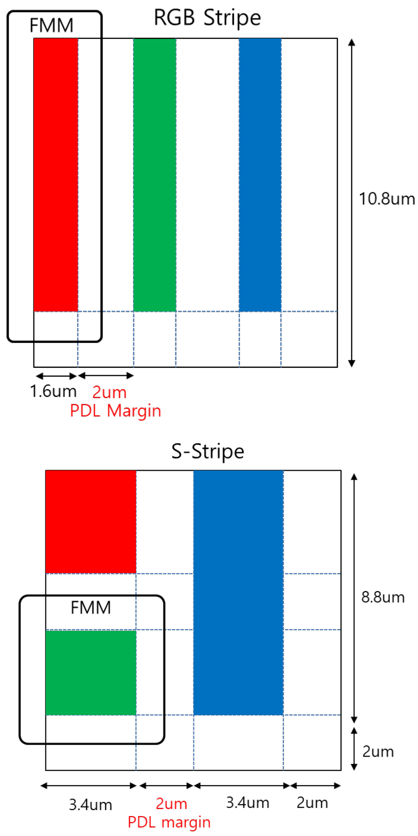


Figure 9. Pixel structure of RGB stripe and S-stripe

In figure 9, pixel structures are compared in terms of the aperture ratio. The aperture ratio of S(Samsung)-Stripe is larger than RGB Stripe. The S-stripe is the OLED pixel structure applied to the early models of Galaxy series to increase the aperture ratio. If we compare these two pixels to our 2400ppi case, the aperture ratio of S-stripe is 45.5% and RGB stripe is 36.2%, respectively, for the case of 2μm PDL margin as described in Table 1. Pixel width of S-stripe is 5.4μm and RGB stripe is 3.6μm, respectively.

In terms of processing with a limited beam size (2~3μm), the processing margin of S-stripe pixel structure is larger, so it can be manufactured with higher yield. Furthermore, since the efficiency and lifetime of blue pixel are relatively low compared to red and green pixels, the efficiency and lifetime of the OLED device can be balanced by increasing the pixel size of blue.

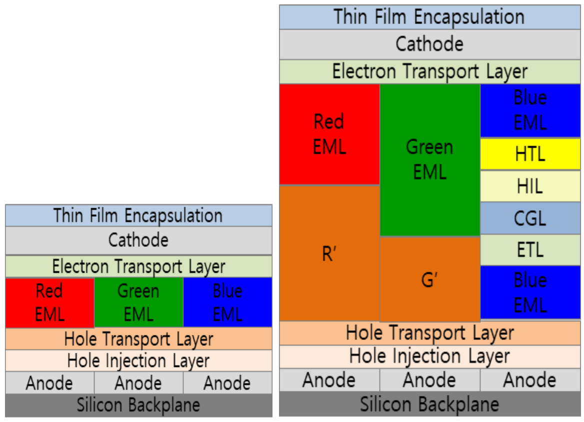
Recently, the efficiency of organic materials shows remarkable efficiency and lifetime by using phosphorescent materials for Red and Green. However, the case of Blue still depends on the fluorescent material, and the efficiency and lifetime are very low compared to Red and Green.

To overcome this, TADF (Thermally Activated Delayed Fluorescence) or Hyper-fluorescence materials are being developed to improve the efficiency of Blue device [7]. In this case, more than three co-deposition process are required, so it is necessary to develop the multiple deposition sources and process for multiple co-deposition. However, increasing the size of Blue pixel size to improve the efficiency and lifetime of the OLED device is still limited until phosphorescent Blue material is developed and commercialized.

Figure 10(a) shows the conventional OLED device structure with top emission. As discussed above, this structure has fundamental limitations in improving the efficiency and lifetime of OLED devices. So, to overcome this limitation, we propose a new OLED structure shown in Figure 10(b). This allows Red and Green to have a single stack, which is an existing structure, while Blue is fabricated as a dual stack to maximize the efficiency and lifetime of the OLED device.

7 Conclusions

The Invar slimming (TCP) and the state-of-the-art UV laser ablation process can realize the ultra-high-resolution (~3,00ppi) FMM fabrication. It is expected that with our ultra-high-resolution FMM sticks, RGB side-by-side OLED micro-display can be mass produced. In addition, if the S-stripe structure, R/G single stack and B dual stack structure proposed by us are adopted, AR applications adopting this RGB side-by-side OLED micro-display is expected to be realized in the near future.



(a) Single OLED device (b) Single R/G and dual stack B

Figure 10. Schematic diagram of (a) conventional OLED device and (b) suggested OLED device

References

[1] G. Haas, "Microdisplays for Augmented and Virtual Reality," SID 2018 DIGEST, pp.506-509 (2018)

[2] P. Wartenberg, M. Buljan, B. Richter, G. Haas, S. Brenner, M. Thieme, U. Vogel, P. Benitez, "High Frame-Rate 1" WUXGA OLED Microdisplay and Advanced Free-Form Optics for Ultra-Compact VR Headsets," SID 2018 DIGEST, pp.514-517 (2018)

[3] T. Fujii, C. Kon, Y. Motoyama, K. Shimizu, T. Shimayama, T. Yamazaki, T. Kato, S. Sakai, K. Hashikaki, K. Tanaka, Y. Nakano, "4032ppi High-Resolution OLED Microdisplay", SID 2018 DIGEST, pp.613-616 (2018)

[4] A. Ghosh, E. P. Donoghue, I. Khayrullin, T. Ali, I. Wacyk, K. Tice, F. Vazan, O. Prache, Q.Wang, L. Sziklas, D. Fellowes, R. Draper, "Ultra-High-Brightness 2K×2K Full-Color OLED Microdisplay Using Direct Patterning of OLED Emitters", SID 2017 DIGEST, pp.226-229 (2017)

[5] C. Kim, K. Kim. O, Kwon, J. Jung, J. Park, D. Kim, K. Jung, J. of SID, "Fine metal mask material and manufacturing process for high-resolution active-matrix organic light-emitting diode displays, pp.1-12 (2020)

[6] K. Kim, C. Kim, J. Park, D. Kim, K. Jung "FMM Materials and Manufacturing Process: Review of the Technical Issues", SID Symposium Digest of Technical Papers, 75-4 (2018)

[7] G. W. Kim, H. W. Bae, R. Lampande, I. J. Ko, J. H. Park, C. Y. Lee, J. H. Kwon, "Highly efficient single-stack hybrid cool white OLED utilizing blue thermally activated delayed fluorescent and yellow phosphorescent emitters", Scientific Report, pp,1-11 (2018