Patterned Black Matrix on Cathode for COE OLED Display

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Abstract
A black matrix (BM) made of Ytterbium nanoparticles (Yb NPs) is patterned directly on the cathode using cathode patterning materials (CPMs). The CPM-Seed and CPM materials ensure high transmittance and low absorption, maintaining display brightness and efficiency. This approach minimizes the gap between the BM and cathode, improving contrast, viewing angles, and optical performance, offering a new solution for advancing the Color Filter on Encapsulation (COE) technology.

Author Keywords
Black Matrix; Color Filter on Encapsulation; OLED Display; Cathode Patterning; Under Display Camera; Under Display IR.

1. Object and Background
Foldable Active Matrix Organic Light Emitting Diode (AMOLED) cellphones have gained significant popularity in recent years. However, a major technical challenge they face compared to traditional rigid AMOLED cellphones is durability. To enhance durability and reduce the bending radius, various designs have been proposed to create stress-neutral planes around weak interfaces such as the OLED/TFE interface. One notable design is the Color Filter on Encapsulation (COE) structure (Figure 1a), which is widely used in commercial products to replace the circular polarizer (C-POL) film.[1,2] The removal of the polarizer (POL-less design) is also essential for improving under-display camera (UDC) performance by increasing panel transmittance, as the typical transmittance of C-POL is only 40–60%.[3] Therefore, COE design also enhances the efficiency and brightness of AMOLED displays, as COE filters much less light than C-POL.

Despite its advantages, COE has notable disadvantages and solutions are still sought-after. The contrast ratio of a display panel is a crucial factor in display quality. Panels using COE designs reflect significantly more ambient light than those with C-POL due to the high reflectivity of the aperture area (areas without a black matrix), making them appear less dark. A black pixel definition layer (PDL) has been proposed to further reduce reflectivity in the COE design,[4] despite the difficulties in patterning the black PDL and its potential to increase leakage current. Still, the reflective cathode, which covers all pixel and PDL areas, remains problematic.

The typical thickness of the TFE is around 10 µm, creating a significant gap between the reflective cathode and the color filter/black matrix plane (see Figure 1a). Transmitted environmental light can become trapped in the TFE layer, leaking through other apertures and worsening diffraction issues, which are harder to compensate for. Moreover, the thick gap can reduce the viewing angle (L-decay) because part of the light may be blocked by the black matrix at various angles (see Figure 1a). Ideally, the thickness between the BM and cathode (d in Figure 1a) should be as small as possible or even zero (see Figure 1b). A proposed solution involves placing the BM and color filters after the first inorganic layer of the entire TFE structure, reducing the gap to about 1 µm.[5] However, this design may cause reliability issues, and the gap, though smaller, still remains.

In this work, we discuss the possibility of utilizing cathode patterning technology that we have developed for under-display camera (UPC) and under-display infrared (UDIR) applications [6,7] to pattern the BM directly on the cathode (see Figure 1c).

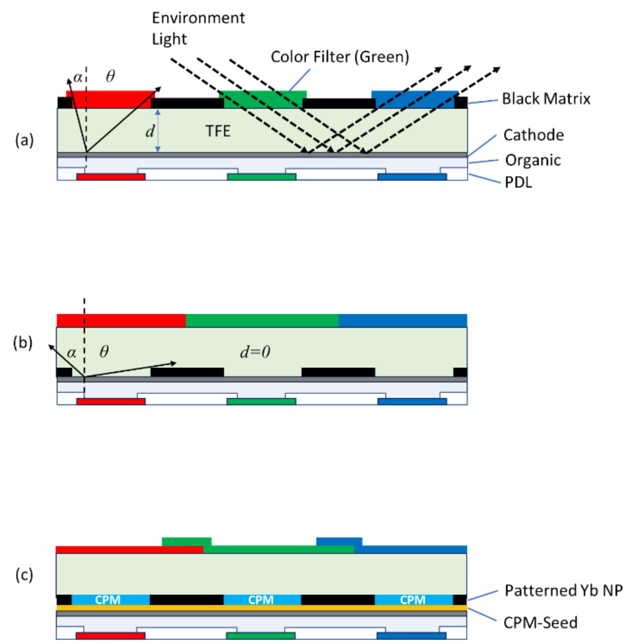

Figure 1. Schematic Cross Section Diagram with different Color-filter (COE) on Encapsulation designs. (a) Traditional design with Black Matrix (BM) on Thin Film Encapsulation (TFE); (b)Preferred design with BM directly on the cathode and under the TFE; (c)Design with BM on cathode achieved with CPM patterning.

2. Black Matrix Material
The material for the black matrix must be sufficiently absorptive—essentially “black” enough. Metals in nanoparticle (NP) form exhibit absorption bands determined by their refractive index and particle size distribution. Ytterbium (Yb) is an excellent candidate because it has high absorption across a broad visible wavelength range when its particles meet certain size distribution requirements. The challenge lies in fabricating Yb NPs in film form, particularly using existing thermal evaporation-based mass production equipment.

Previously, we developed cathode patterning materials (CPMs) for UDC and UDIR applications using a material development platform that integrates artificial intelligence (AI) and quantum computing. Using the same platform, we successfully developed CPM-Seed, a material that serves as a seed layer for forming Yb

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NPs with the desired size distribution. CPM-Seed is an organic material similar to CPM and can be evaporated using standard OLED mass production tools with linear evaporation sources. When tens of nanometers of Yb are deposited onto a CPM-Seed layer of 10–20 nm, a highly absorptive Yb NP film is formed.

The key property of the black matrix to focus is its reflectivity. To demonstrate the concept, we fabricated a device with the structure of Glass / Ag (80 nm) / HTL (170.0 nm) / Mg:Ag (1:9, 10.0 nm) / CPM-Seed (15.0 nm) / Yb (70.0 nm) / CPL (50 nm). This structure mimics an actual OLED device with a thick reflective Ag anode and a thin MgAg cathode. As shown in Figure 2, the reflectance of the sample is less than 5% over the entire visible wavelength range. The inset in Figure 2 shows a photo of the sample (about 0.5 cm × 1 cm), illustrating its visual darkness.

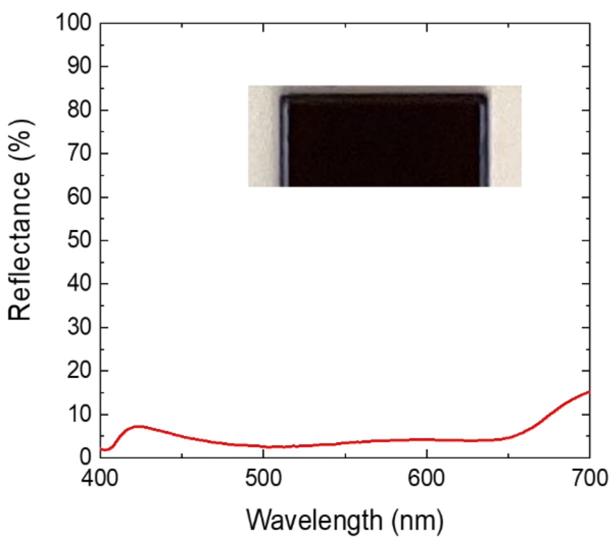

Figure 2. Reflectance of the sample with a device structure of Glass / Ag (80 nm) / HTL (170.0 nm) / Mg:Ag (1:9, 10.0 nm) / CPM-Seed (15.0 nm) / Yb (70.0 nm) / CPL (50 nm). The inset is the actual photo of the sample.

3. Black Matrix Patterning with CPM

The next step involves determining how to pattern the black matrix made of Yb NPs. As mentioned earlier, we developed CPM materials for patterning the Yb/MgAg cathode, where a thin layer of Yb (1–2 nm) as an electron injection layer (EIL) is already included. The new CPM design must handle 10–100 nm of Yb deposition without sacrificing transmittance, expanding the process window for Yb deposition.

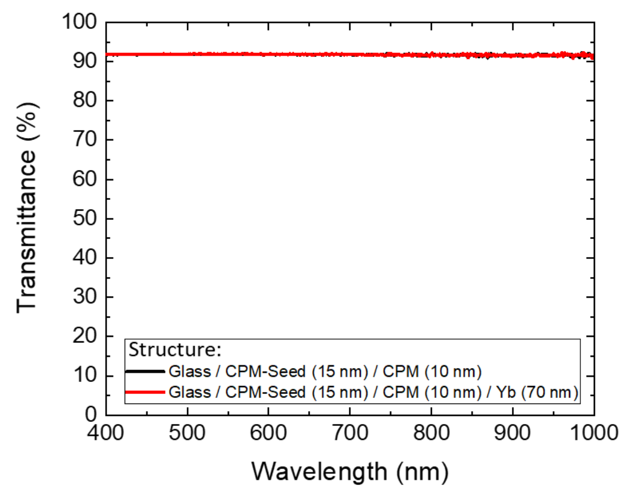

Figure 3. Transmittance of the sample with a structure of Glass / CPM-Seed (15.0 nm) / CPM (10 nm) / Yb (0 and 70.0 nm) / CPL (50 nm).

The patternability of thick Yb using the new CPM was tested and shown in Figure 3, which compares the transmittance of two device structures—with and without 70 nm Yb deposition. The almost complete overlap of their transmittance curves indicates that CPM has excellent patternability for Yb up to at least 70 nm. In thin-film science, the substrate's properties greatly influence the deposited thin film. Therefore, a 15 nm CPM-Seed layer that is needed for forming Yb NP film were inserted before the CPM layer in both cases.

Figure 4 summarizes the Yb NP patterning process. After OLED fabrication (up to the cathode layer), a thin CPM-Seed layer is deposited using an open mask, followed by CPM deposition with a fine metal mask (FMM), and finally, a thick Yb layer is deposited with an open mask. This process ensures that only areas without CPM form the highly absorptive Yb black matrix.

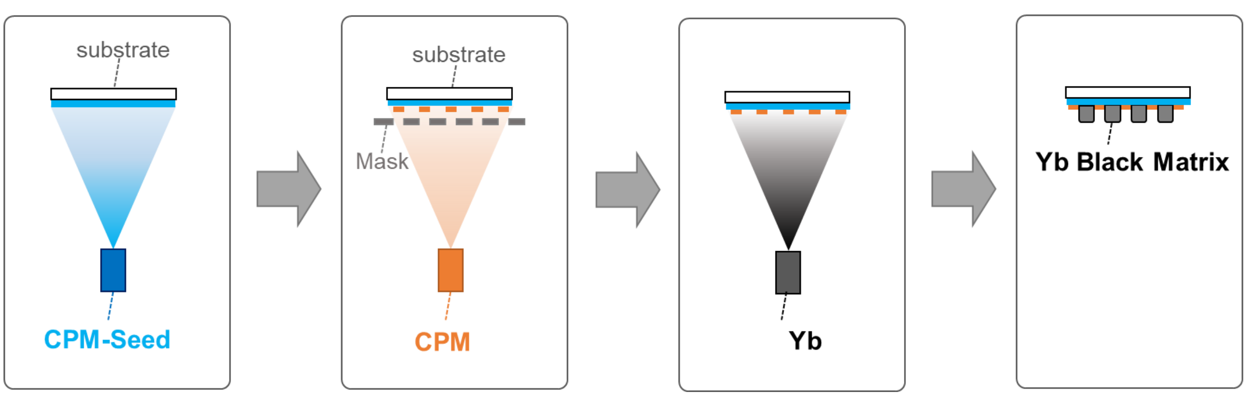

Figure 4. Schematic diagram of the Yb Black Matrix patterning process.

4. Further Discussion

Since CPM-Seed and CPM are deposited over the active pixel area, their transmittance is crucial to OLED performance. If the CPM-Seed absorbs too much light, it may reduce the panel's current efficiency and brightness. Figure 5 shows the transmittance of CPM-Seed and CPM layers compared to a reference glass substrate. Same thickness (see Figure 3) was used to be consistent. The overlapping curves confirm the high transmittance and low absorption of both materials.

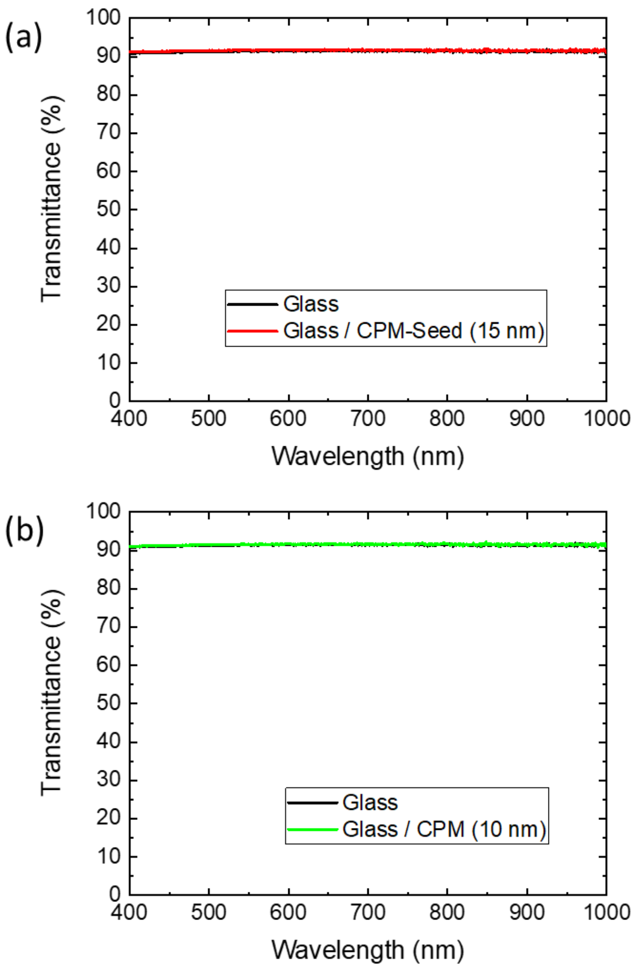

Figure 5. Transmittance of (a) 15 nm CPM-Seed on glass and (b)10 nm CPM on glass along with the transmittance of the respective glass reference

Two possible design architectures exist: fabricating the BM either before or after the CPL capping layer. In both cases, the CPM-Seed/CPM is adjacent to the CPL layer. Therefore, the refractive index of CPM-Seed and CPM must be optimized for maximum optical out-coupling. For example, if the CPM-Seed/CPM is deposited before the CPL, a low index CPM-Seed and CPM may be beneficial as a low/high bi-layer CPL. Otherwise it is more preferable to have a high index CPM-Seed/CPM to match the refractive index of the CPL layer, i.e. becoming part of the CPL. Either way, fine-tuning is necessary to optimize the performance.

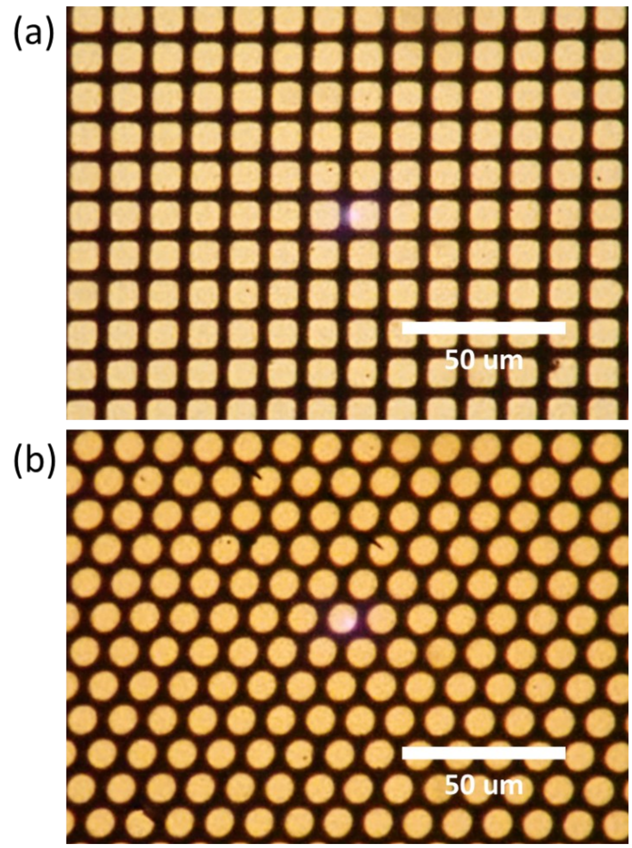

Figure 6. Microscopic photos of samples to demonstrate the Yb black matrix with super higher resolution.

Two samples with different aperture opening layouts were fabricated using a common device structure of Glass / CPM-Seed (15.0 nm, common open mask) / CPM (0, 15 nm, FMM) / Yb (70.0 nm). The microscopic images of the two samples are shown in Figure 6. The successful demonstration of the high ppi (> 2000 ppi) Yb BM in Figure 6 indicates that the patterning process and the material system have no limitation on achieving the extremely high resolution. Although the resolution of most foldable panels in the market is only about 380 ppi, it is still a process challenge to guarantee that the CPM is only deposited over the pixel area without encroaching too much on the non-pixel area. Tighter control of the FMM aperture size and alignment accuracy is necessary. Figure 1c shows a proposed design using the Yb NP black matrix in the COE structure. Beyond depositing the black matrix on the non-emissive bank area above the cathode, reflectivity can be further reduced by overlapping the color filter with the non-emissive areas of the panel.

5. Conclusion

We have demonstrated that CPM-Seed and CPM materials can be used to pattern a low-reflectivity black matrix made of Yb NPs with very high resolution. The optical properties of these materials are compatible with existing OLED structures. This black matrix design can be applied to the COE structure, eliminating the gap between the black matrix and the OLED cathode, enhancing durability and display performance.

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