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High Resolution Photolithography for Direct View AMOLED AR Displays

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Abstract

High resolution RGB OLED frontplane is a key enabler for direct-view transparent AR displays. 1250 ppi passive displays and semi-transparent active displays are shown. T90 lifetime at 1000 nit is above 150 hours after patterning. OLED photolithography can provide pixel density above 1000 ppi while keeping high aperture ratio.

Author Keywords

RGB OLEDs; photolithography; AMOLED displays; ultra-high resolution.

1. Objective and Background

Augmented reality (AR) has become more than just a buzzword, with most of technology companies foreseeing different headset components in their product roadmaps. The format of smartglasses is one of the proposed implementations to continue the personalization of computing and communication, following the “personal computer – laptop – smartphone” line of heritage. As such form factor is very demanding, especially for consumer electronics, each component needs to be rethought and redesigned – new miniaturized versions of memory, battery, connectivity, logic, sensing and interfacing are required, keeping mass manufacturability and supply chain in mind. Specifications for an AR display are extra demanding since this is the dominating user interface.

The near-to-eye format of AR displays imposes ultra-high definition, as the pixel density needs to be beyond the pattern resolving capabilities of the human retina (30 cycles per degree) [1,2]. The resolution should be maximized to provide the highest possible output within the eye box in any given point of the 180° field of view (FOV), also to enable foveated rendering. Aperture ratio close to unity will eliminate the screen door effect and ensure natural experience. Transparency is necessary to avoid sense of isolation from the real-world view and to diversify from the virtual reality (VR) headsets (Fig. 1). To realize all of the above, we need both the microdisplay-like pixel pitch down-scaling (CMOS background [3]) and the flat-panel-display-like (FPD) backplane size up-scaling (TFT background [4,5]). Switching to advanced nodes in flat panel backplane manufacturing can result in ultra-high definition, direct-view AR displays fabricated in a cost-effective way.

Once an appropriate backplane is provided, the frontplane technology must be chosen (Fig. 2). With OLEDs starting to dominate the smartphone display industry not only with performance but also with the cost structure, a suitable hi-res pixel technology must be established for OLEDs. In this paper, we describe how side-by-side multicolor OLED patterning by photolithography can address the needs of the future AR displays. The relevance and maturity of different parameters are explained, and examples of early implementations are described.

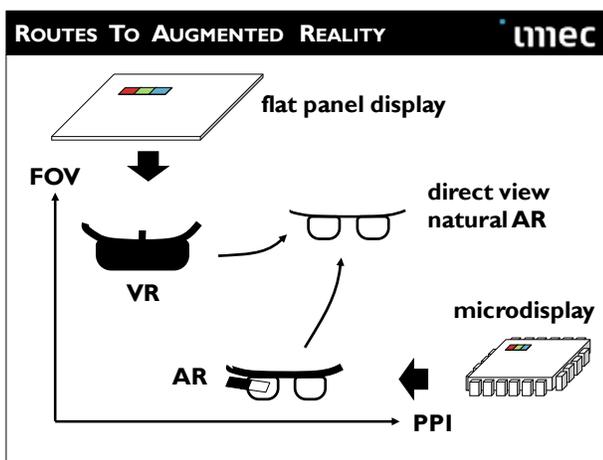


Figure 1. Head-mount display implementations Future augmented reality display should combine the benefits of both flat panel displays (size, transparency) and CMOS-based microdisplays (pixel density).

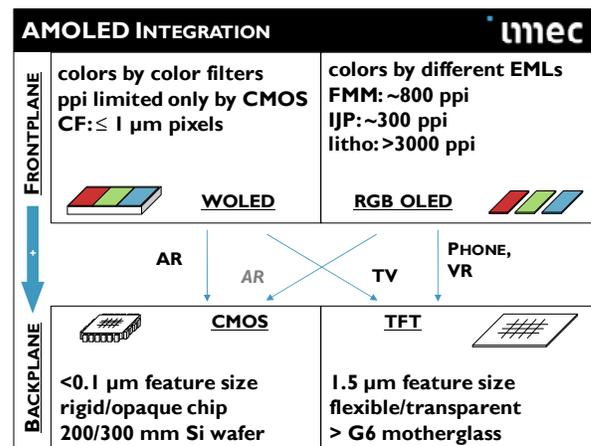


Figure 2. Integration options in AMOLED displays Color-by-white vs. RGB OLED frontplane can be fabricated on top of CMOS or TFT backplane. Each combination is suitable for different applications.

2. Results and Discussion

2.1 Resolution and aperture ratio

Patterning OLEDs by photolithography is an emerging fabrication technique. Since OLED materials are extremely fragile, proper choice of photolithography chemistry is necessary, with fluorinated [6] or non-fluorinated systems [7] as options. In this work, we describe an update of our work with a chemically amplified, i-line photoresist (Fujifilm OSR). This system allows pattern transfer down to 1 μm, for positive and negative layouts (Fig. 3). Transfer of small islands means that, with appropriate alignment (for example with an i-line stepper), pixel density of a few thousand pixel per inch (ppi) can be realized. Transfer of holes means that pixel spacing can be minimized, resulting in high aspect ratio.

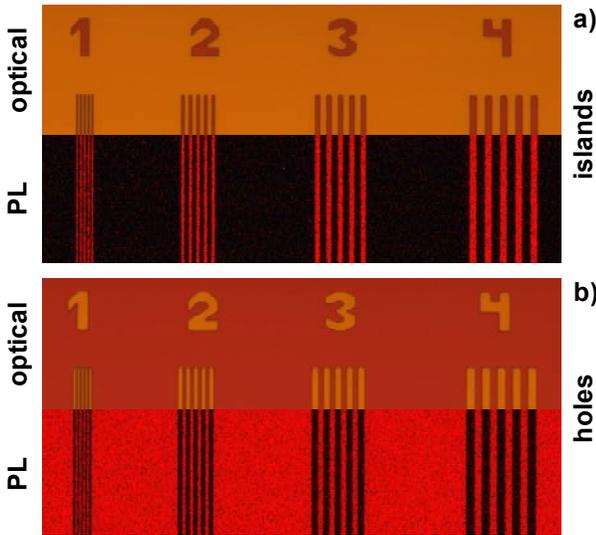


Figure 3. OLED patterns of 1 μm
Optical and corresponding photoluminescence pictures of green OLED patterned as islands (a) and holes (b).

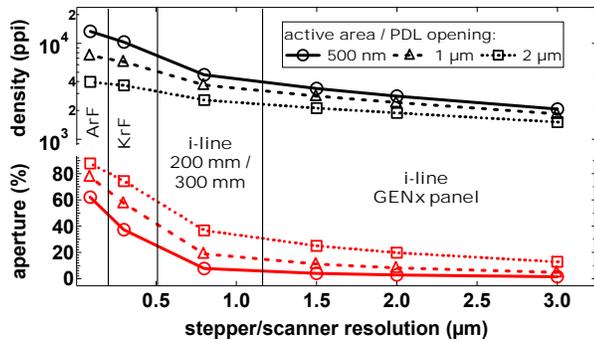


Figure 4. OLED lithography node effect
Pixel density and aperture ratio achievable for different exposure tools (for specified EL area).

The achievable pixel density of the frontplane is limited not only by the OLED photoresist but also by the critical dimension (CD) and alignment accuracy of the litho tools used (Fig. 4). In FPD i-line steppers (panel manufacturing), the achievable CD is 1.5 μm (with 0.25 - 0.5 μm overlay), while CMOS fabs (microdisplay manufacturing) feature also more advanced

semiconductor nodes (with 248 nm KrF or 193 nm ArF light source). Assuming a minimum PDL opening (defining the active area) of 500 nm, a 1.5 μm node imposes a density limit of 3500 ppi (for RGB) with aperture ratio below 5%. Going to KrF steppers, the achievable density increases to 10000 ppi while keeping the aperture ratio above 35%. This points to the need of tooling upgrade for the future AR displays, both for front- and backplane. Denser and more efficient packing of pixels requires scaling down the FPD technology node.

2.2 Lifetime

OLED patterning by photolithography means that the deposition of the stack is interrupted (vacuum break) and the water-based photoresist system materials interact with the organic materials. In our case, the entire photolithography process is performed in a 200 mm cleanroom in ambient atmosphere. The devices are loaded back into the glovebox after the etch step for each color and after the photoresist strip when all colors have been realized. This poses a serious challenge for the device lifetime – the first version of our patterned OLED showed electroluminescence, but the brightness dropped to zero already after few minutes (Fig. 5). Since then, we have introduced several improvements of the photoresist, OLED stack [8] and fabrication process, resulting currently in a phosphorescent green OLED with T90 lifetime of > 150 hours at the starting brightness of 1000 nit (Fig. 6). Efficiency remained above 85 cd/A before and after patterning.

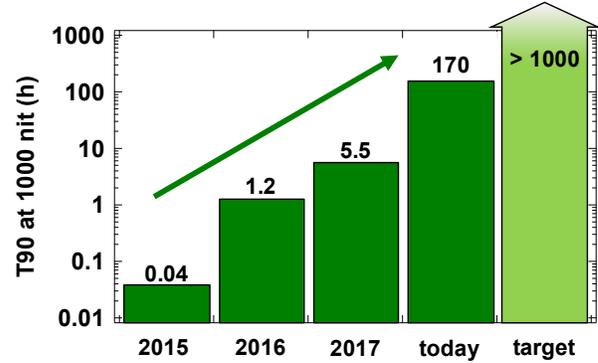


Figure 5. Progress of patterned OLED lifetime
Current baseline phosphorescent green OLED with 170 h T90 at 1000 nit, with target > 1000 h.

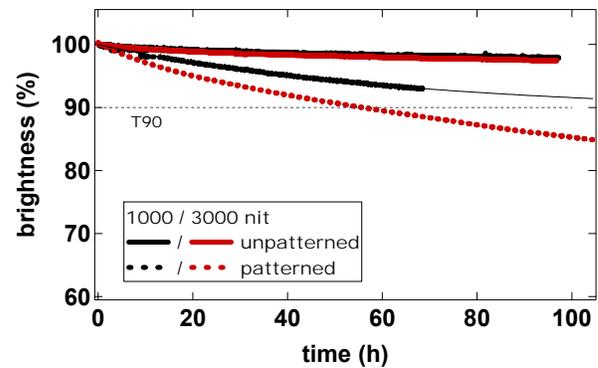


Figure 6. Lifetime curves at 1000/3000 nit
Phosphorescent green OLED brightness degradation starting at 1000 nit (black) and 3000 nit (red).

2.3 Integration

Patterned OLEDs were implemented in passive displays with an array of 1400x1400 pixels (1.96 megapixels). GEN1 glass plates (35x32 cm²) are used as substrate with 6 μm metal lines and 10 μm line pitch (Fig. 6), with SiN pixel definition layer (PDL) deposited and patterned on top. After dicing, green and red OLED stacks are deposited by thermal evaporation. After deposition of the first color until at least emission layer (EML), photoresist is spin-coated, baked, exposed and developed. Then, the OLED stack not covered by the photoresist is dry etched. After etching, the sample goes back to the ultra-high vacuum chamber for second color deposition and the patterning process is repeated, this time finishing with stripping the photoresist. Semi-transparent top contact stack is subsequently deposited and the display is encapsulated with cavity glass.

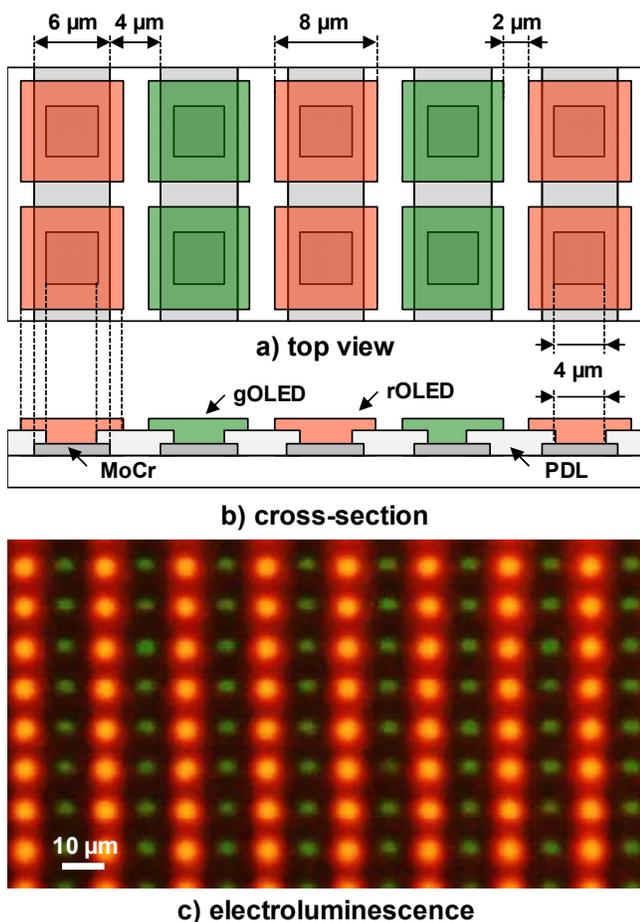


Figure 7. Pixel design in a two color 1250 ppi display Schematic top view (a) and side view (b) of a passive display designed for OLED patterning, with EL image of the working array (c).

Bottom electrode design allows for separate driving of both colors, while PDL design allows for emission of a fixed image specified for each color (Fig. 7). A custom designed driver box (15x10x4.5 cm) allows for portable demonstration with a USB power bank as the supply. Subpixel pitch of 10 μm results in smooth edges and excellent feature representation. The aperture ratio of 16% is chosen to ensure 100% pixel yield (with overestimated overlaps) which is limited by the contact aligner

feature size and alignment accuracy (0.85 μm). The device has been tested for approximately 40 hours with both colors on with no noticeable drop of brightness nor appearance of defects. The fabrication process is compatible with both CMOS backplane and flexible TFT backplane, thus such frontplane can be implemented in an active matrix display. Two colors are used instead of three (RGB) for the simplicity of the fanout (single metallization).

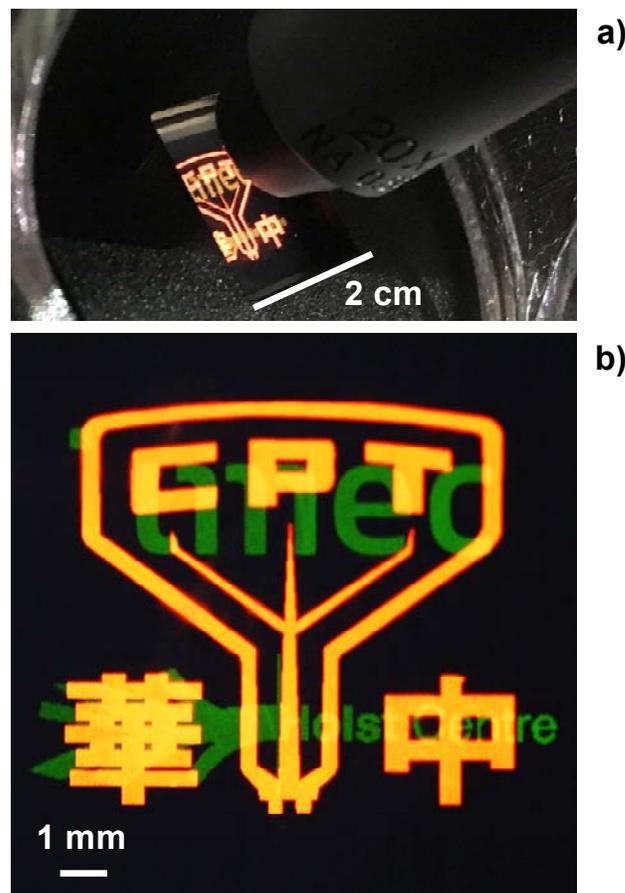


Figure 8. Passive 1250 ppi patterned OLED display 1400x1400 pixel array with 10 μm subpixel pitch and independent color driving: system view (a) and close-up of the active area during operation (b).

2.4 Transparency

FPD displays can be made transparent, with several demonstrations of high-end devices from top panel makers. Here, we demonstrate a simple semi-transparent display where the see-through capability was realized by increasing the spacing of RGB pixels (Fig. 8). A TFT pixel engine with self-aligned thin-film transistors (SAL TFT) was used, based on amorphous indium gallium zinc oxide (IGZO, mobility 15 cm²/Vs) and fabricated using the GEN1 pilot line.

Display transparency drops to ~93% due to two air / glass substrate interfaces and further to 83% due to absorption in the metal fanout structure. Line thickness is minimized to the critical dimension of the FPD tools used. With patterning of the OLED stack, not only side-by-side RGB pixels are enabled, but the OLED stack can be confined to a minimum overlap around

the pixels. The largest transparency drop is due to the semi-transparent metallic top contact which reduces the transmission to approximately 50% if no anti-reflection layers are used. At this point, monochrome green displays are presented (Fig. 8), with the full color display as the next implementation (3 subpixels are foreseen in the design). For a true transparent panel, the backplane TFTs need to be scaled down (e.g. to a compact 2T1C architecture with minimum feature size) to take advantage of the smallest achievable OLED size.

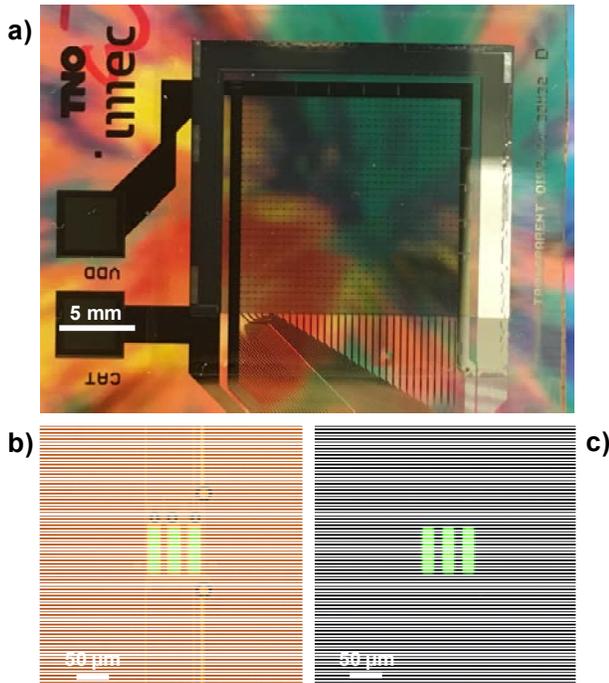


Figure 9. Semi-transparent AMOLED display
Transparency is achieved by distributing the pixels, thus dramatically reducing the aperture ratio: top view (a), pixel detail (b) and respective EL image (c).

3. Conclusions and Outlook

Direct view, transparent displays for augmented reality need ultra-high pixel density with maximized brightness and aperture ratio. Patterning OLED stacks by photolithography is one of the enabling technologies for realization of displays above 5000 ppi. This holds assuming a backplane with sufficiently high ppi is provided and that appropriate litho tools can be used to minimize the feature size and overlay.

OLED lifetime after patterning, a key parameter for industrialization, has been encouragingly increasing and is now above 150 hours for T90 at 1000 nit. The next planned experiments include analysis of lifetime for the same stack patterned twice and thrice, emulating exposure to the patterning process of different colors. In such case, a vacuum reference is a benchmark for patterned devices. Using the same stack several times provides the degree of degradation for each step (“color”).

For two color devices, a demo display with 1250 ppi and two independently driven phosphorescent OLED stacks has been operated for more than 40 hours without degradation. The results described in this paper were obtained using the “ambient worst-case scenario”, which means that none of the litho tools was equipped with inert gas enclosure and that shared research tools were used. With a dedicated toolset, the lifetime is expected to further bridge the gap to the target of several thousand hours T90. As the next step in lifetime improvement, driving voltage will be optimized – current OLED stacks show increase of driving voltage between 50% and 100% after patterning, indicating charge carrier balance issues that still need to be resolved.

The test structures described in this paper are used for verification of the frontplane patterning technology with custom designed backplanes. At this point, no major issues with integration have been encountered. With AR headsets becoming a plan rather than a vision for many key industrial players, realization of displays with extreme pixel density becomes a crucial enabler.

4. Acknowledgements

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