Island and Hole Fabrication on OLED Stack for High-Resolution Sensor in Display Application

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Keywords: Sensor, OLED, Photolithography

ABSTRACT

Advances in mobile and wearable electronics have driven the integration of multi-functional devices, such as sensors and display, to enable new form factors in next-generation electronics. In this presentation, we will show our results in photolithography patterning of OLED stack to create islands and holes structure for the sensor in display applications.

1 INTRODUCTION

Advances in mobile and wearable electronics have increased our need for a better user interface for human-computer interaction. The integration of multiple devices, such as sensors and display, is essential to enable new form factors in innovative mobile and wearable devices. High screen to body ratio of the mobile display is one of the critical factors for high-end mobile phone products. The industry is inventing multiple ways to hide the front-side camera and fingerprint sensor in the screen without degrading the display image quality [1-2].

In the current organic and hybrid electronic fabrication, fine metal mask (FMM) method is widely used in the AMOLED display to create red, green, and blue EML patterns in the OLED stacks to render full-color space. Displays with more than 500 ppi pixel definition are commercialized, and >2000 ppi OLED pixel with SiNx based membrane are also under development [3]. Nonetheless, there are also drawbacks to hamper the technology to go for large substrate size and higher aperture ratio at high resolution due to mask sagging and shadowing effects [4], respectively. It is not possible to create a hole structure via FMM methods. The cleaning steps and replacement of the FMM also make it hard to reduce the running cost of this manufacturing route.

The industry also investigates routes in solution printing manufacturing process such as inkjet printing (IJP). More than 150ppi AMOLED demonstrators are shown by multiple companies [5]. The substrate size is not limited, and there are several research directions in improving the printing resolution, such as aerosol jet [6] or electrostatic jet printing [7]. However, there are still challenges such as layer thickness uniformity in large area deposition and the lower reliability compared to evaporated OLEDs [8].

Alternatively, photolithographic patterning has been widely applied in the inorganic semiconductor industry for decades. Si transistor with a gate length of 5nm is closed to be commercialized for high-performance computing. Photolithographic patterning enables the freedom of layout design compared to FMM and IJP with higher resolution. One challenge to applying photolithographic patterning to organic and hybrid electronics materials is the chemical compatibility of the organic semiconductor to the photolithography related chemical products. Another difficulty could be the fragility of organic and hybrid electronic materials in a conventional photolithographic patterning environment. A novel photolithography technology is needed to enable the photolithography process on organic hybrid electronics for higher scaling and integration level.

imec has been working on the photolithographic patterning technology for organic semiconductor to realize high integration level of organic transistor (OTFTs), organic photodiodes (OPDs), and OLEDs [9]–[11]. We work with industrial partners to co-develop the necessary process, photoresist products, and device structure to enable the photolithographic processes on

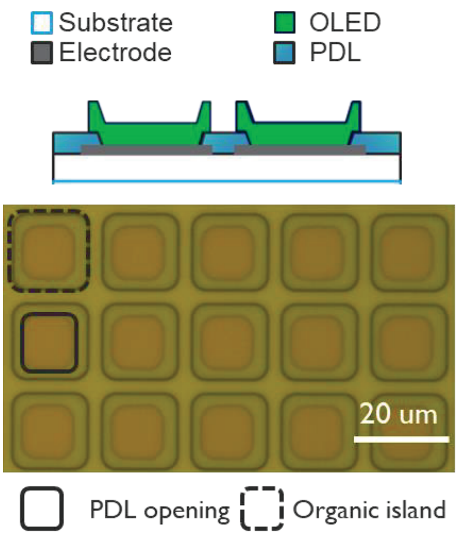


Fig 1. Schematic and microscope image of OLED islands on top of the PDL opening.

organic and hybrid electronics.

In this presentation, we will show our results to create organic islands and open holes through OLED stacks via photography. The first part of the work is related to the OLED island fabrication by photolithography and its application toward high-resolution OLED pixels. We show very low device lifetime degradation after the photolithography patterning process in ambient environments. We also present the device characteristics after multiple OLED patterning. In the second part of the publication, we show our work related to hole opening by photolithography for the under-display imager application. The goal is to locally increase the transparency of an OLED stack for target wavelength without jeopardizing the display image quality. The OLED characteristics with and without hole patterning are also under investigation.

2 EXPERIMENT and RESULTS

2.1 OLED islands fabrication for high-resolution pixel

The patterned organic islands on top of the PDL opening are shown in Fig. 1. The organic island can be isolated nicely by photolithography patterning. In this test vehicle layout, the pixel pitch is 20 μm with PDL opening with a side length of 10 μm. For full-color R-G-B side-by-side OLEDs pixels, it is necessary to develop multiple photolithographic processes and etchings [11]. The schematic process flow to fabricate test samples to study the effects of multiple photolithographic patterning on OLED is shown in Fig 2. All the organic layers are deposit in a vacuum chamber at a base pressure of 10^{-7} torr. To fabricate 2x patterned samples, we take a 1x patterned sample without stripping for the following processes, including the 2nd OLED deposition and photolithographic process. After all the photolithographic process, the top electrodes are deposited all together in a metal chamber.

The EL spectra and J-V-L of the OLEDs after

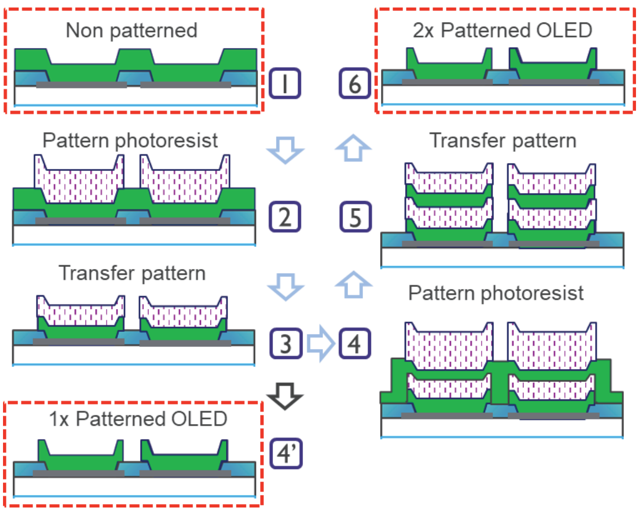
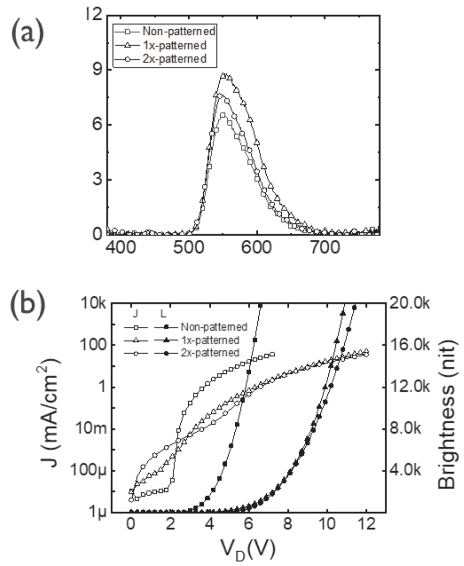


Fig 2. The schematic flow to fabricate non-patterned, 1x patterned, 2x patterned samples



Characteristic @ 1000 nit	V (V)	cd/A	EL peak/FWHM (nm)
Non-patterned	3.6	96	550/75
1x-patterned	6.6	86	550/75
2x patterned	6.6	87	550/75

Fig 3. (a) The EL spectra (b) the J-V-L characteristics of non-patterned, 1x patterned, 2x patterned samples

different patterning process are shown in Fig 3. The peak wavelength of the OLEDs EL spectra, as shown in Fig 3(a) is at 550 nm with FWHM of 75nm. The emission spectra of non-patterned, 1x-patterned, and 2x-patterned devices are identical. There is no impact on the EL spectra due to the photolithography process. The non-patterned device shows a driving voltage of 3.6V with an efficiency of 96 cd/A at 1000 nit. The OLED characteristics of the 1x and 2x patterned OLED are very similar. Both cases show a driving voltage of 6.6V and an efficiency of 86 to 87 cd/A. The increase of driving voltage and reduction in efficiency might be due to the degradation of the charge transport properties of the organic semiconductor layers. There might be additional trap states that are generated during photolithography processes. It is interesting to see the characteristics of 1x patterned and 2x patterned OLEDs are quite similar. It may imply that the primary degradation of the OLED characteristics is coming from the organic/photoresist interface during the process in the test vehicle. The root causes and the locations of the deterioration in the OLED stacks are under further investigation. The device lifetime curves measured from 1000 nit are shown in Fig 4. All the curves show a similar degradation trend with T95 > 200 hours. The data is 3x improved compared to the previous report values [11]. The improved lifetime of the photolithographic patterned OLEDs shows the potential of the technology for future OLED fabrication.

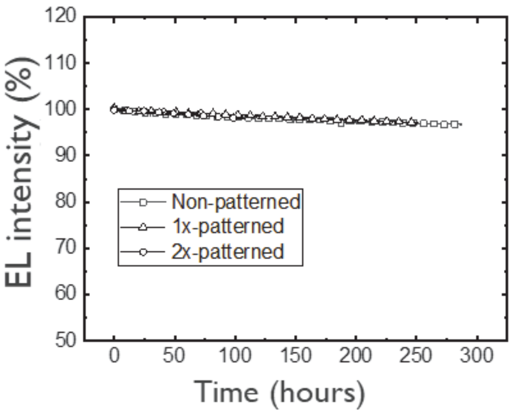


Fig 4. OLED device lifetime at 1000nit of non-pattered, 1x patterned, and 2x patterned devices, respectively.

2.2 High-resolution hole array through OLED stacks

For the under-display imager application, it is crucial to locally enhance the transparency of a display for the target wavelength. In our previous work for transparent display study, we study the impacts of each layer in a display stack to the transparency of the display. We learned that the most crucial layer is the thin Ag layer in an OLED stack that reduces the transparency dramatically, especially for the longer wavelength region [12]. One method is to remove the thin Ag layer locally. It is not straight forward to create hole structures via FMM or IJP. Thus, it is essential to develop technology to enhance the transparency of the display stack for various imagers under the display. On the other hand, it is possible to create hole structures by photolithography patterning via changing the mask polarity. Here we develop an RIE recipe to pattern and organic/Ag/capping stack to create a high-resolution hole array on OLED stacks via photolithography patterning.

To develop the etching recipe for an OLED stack. We prepared samples on top of ITO glass with organic layers/Ag(20nm)/capping layer on top. The schematic stack composition is shown in Fig 5(a). We apply a mask with a pitch of 20 μm and an aperture ratio of 81%, aiming to increase the transparency by photolithographic patterning. The microscope image of the patterned sample fabricated by the optimized recipe is shown in Fig 5(b). We successfully open a hole array via photolithography to increase transparency. The transparency of the samples before and after patterning is shown in Fig 5(c). The transparency at longer wavelength increased largely from < 20% to > 70%. With the developed recipe, we design a new layout to open a hole every 4 pixels to mimic the under-display imager case shown in Fig 6(a). The microscope and AFM images of the patterned OLED samples are shown in Fig 6(b) and Fig 6(c). We successfully open a hole array through a phosphorescent green OLED stack. The AFM image indicates the OLED stack in the opening area is completely removed.

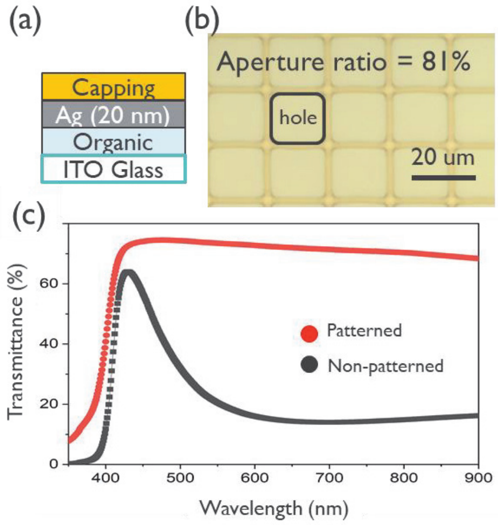


Fig 5. (a) Schematic of organic/Ag/Capping stack to be patterned (b) microscope image of patterned stack (c) transmission spectra of patterned and non-patterned samples

The device characteristics before and after hole opening are shown in Fig 7. We did not see considerable degradation in the OLED performance, although there is a slight increase in driving voltage. The excess driving voltage of the OLED devices after photolithography at 1000 nit is about 0.6 V. It is interesting to see the voltage increase was smaller compare to the previous case when we patterned OLED island. It might be because the photoresist is in contact with the capping layer instead of direct contact with the organic semiconductor. The efficiency versus brightness, EL spectra, and device lifetime measurement with and without photolithographic patterning is shown in Fig 7. There is no significant degradation in the patterned OLED.

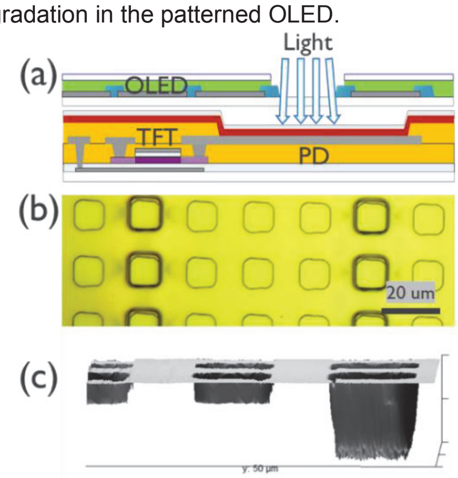
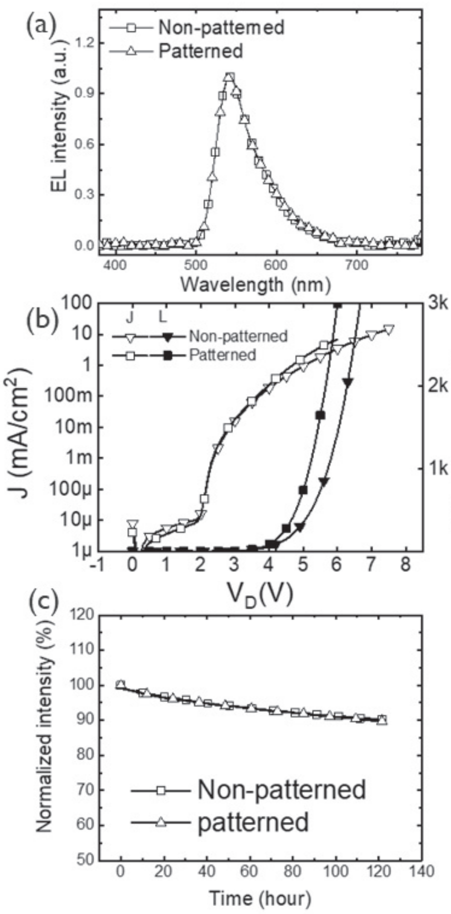


Fig 6. (a) The schematic of the under-display imager application with OLED stack with hole openings (b) Microscope image of an OLED array with hole openings (c) AFM image of the patterned OLED stacks



Characteristic @ 1000 nit	V (V)	cd/A	EL peak/FWHM (nm)
Non-patterned	5.2	42	541/58
Patterned	5.7	40	541/58

Fig 7. (a) The EL spectra (b) the J-V-L (c) the device lifetime at 1000 nit of non-patterned and patterned samples.

3 SUMMARY

We developed a photolithography patterning process to create OLED islands and holes for different applications. The OLED characteristics of OLEDs experienced by multiple photolithographic patterning are studied. The main degradation in the characteristic is the excess of driving voltage, while the spectra, and most importantly the lifetime are similar for non-patterned and patterned devices. The OLED performance of 1x patterned and 2x patterned devices are similar, which may indicate the degradation happened close to the organic/photoresist interface. With the same photoresist system, we also demonstrated a high-resolution hole array with a side width of 10um. The OLED device characteristics with and without hole patterning are nearly identical with a slight increase of driving voltage. The less excess driving voltage after the photolithography process compared to the OLED island case is in line with the assumption that the source of the excess of driving voltage is due to the direct exposure of photoresist products on top of organic semiconductor during the photolithography process. The findings are valuable to develop methods to reduce OLED degradation further and open a new route for OLED fabrication.

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