Co-Integration of Organic Photodetector with MicroLED Dedicated to Multifunctional Display Application

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Abstract

MicroLED is seen to be a promising technology for future display. However, traditional display technologies are making progress and are currently challenging the intrinsic performances of MicroLED for traditional display. One competitive advantage of MicroLED remains in its exceptional high radiance requiring less active light emitting surface. This unique property paves the way of disruptive display features such as embedding sensors in the same display plane to create multifunctional display. This paper tackles the question of technological co-integration of MicroLED and Organic PhotoDetector (OPD). Relying on measurement results on a custom co-integrated device, this paper provides performances of MicroLED (radiance, radiation pattern) and OPD (responsivity, dark-current) to evaluate the effect of co-integration. We pay a specific attention to cross-talk coupling that remains a bottleneck of co-integration.

Author Keywords

MicroLED; OPD ; multifunctional display; cross-talk; in plane sensing.

1. The trends of multifunctional Display

1.1. Context

Smartphones, laptops, and many other screen devices have become integral parts of our lives. Over the last few years, display devices have evolved to include more sensors that enhance the user's experience and security. Sensing functions include touch, fingerprint (1), proximity sensing, light sensing, 3 dimensional (3d) sensing (face, gesture recognition), eye tracking, temperature sensing, health monitoring (2), lensless cameras, antennas, and even micro-piezo elements for integrated speakers or pressure sensing (3). More precisely among the potential applications, some are highly promising and worth highlighting. Fingerprint sensors can be over the entire display area to sense the whole finger or multiple fingers at once, significantly increasing security. Using infrared (IR) sensing also could provide access to vein imaging, for example, at the same time or mid-distance gesture-recognition modality (4). Also, biomonitoring could enable multiple parameters (e.g., body temperature, heart rate, blood oxygen, vein imaging, photo-plethysmography, and electrocardiography) (5).

Currently, most of the sensing architecture is composed of many discrete components that are located in the bezel of consumer devices preventing the display from covering the full smartphone surface. Originally positioned outside the display, sensors have progressively been embedded under the display for the sake of compactness. This poses difficulties, as the display then must allow an additional optical signal to cross through it, affecting image quality. An alternative option would consist in integrating sensors within the display, directly onto the front plane panel (6).

1.2. MicroLED for multifunctional display

As detailed in our previous work (7), in existing OLED and LCD displays, the pixel area is covered almost fully by the electro-optical elements to provide enough luminance. Whereas in MicroLED displays, the light source is so powerful that only a limited emitted surface is required and only a small part of the total pixel area is exploited providing thus free space (5). This free space could be used to add new devices to provide additional functions to the display opening a world of opportunities to merge sensing and displays into a single device. As MicroLED technologies mature, moving the sensor from under the display directly onto the front plane would eliminate any obstruction from the display and shrink total device thickness. Therefore MicroLED is well suited for multifunction displays.

Also, MicroLED needs to compete with currently widely spread LCD or OLED technology. As state in some market studies (3) (8), there is a strong interest for MicroLED to demonstrate a differentiation factor in order to enhance market share. Multifunction display would be one of them and could offer new opportunities for MicroLED industry (6).

1.3. Background

Related to multifunctional display solution, most of current development relies on OLED as illumination source and OPD as photodetector. As we compared in our previous work (7), combining the OPD pixel within the same plane as OLED the addition of the sensor will imply to reduce the emitting area whatever the type of arrangement. Therefore, the brightness of the display or alternatively the photodetector area will be trade off with the system sensitivity. As above mentioned, because of its brightness, multifunctional display based on MicroLED does not suffer from this compromise. Some recent works have been presented to leverage this MicroLED advantage mainly focusing on architecture or MicroIC consideration (7) (9) (10). Unlike, this paper focus on technology co-integration between MicroLED and photodetector, and more precisely organic photodetector.

1.4. Outline

This paper starts by describing a custom device where MicroLED blocks and OPD blocks are co-integrated. Challenges of co-integration between MicroLED and OPD are risen and we give some insight how we tackle them from technology point of view. Then, measurement results of MicroLED performances such as radiance and radiation pattern are provided. OPD performances in term of responsivity and dark current are also given. Co-integrated and standalone version of the OPD are compared. At last, we pay specific attention to cross-talk measurement setup so as to extract the effect direct coupling between MicroLED and OPD depending on their proximity.

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2. MicroLED & OPD co-integration

2.1. Device description

We develop a custom device relying on a specific arrangement of co-integrated MicroLED blocks and OPDs blocks. In (11), we recently demonstrated the co-integration capability between MicroLED and OLED. In the context of multifunctional display application, in this article, we study the benefits of the co-integration between MicroLED and OPD. Each MicroLED blocks is composed of 800 individual MicroLED of 35x35µm² commonly driven. The overall emitting surfaces is 0,85 mm² while the OPD surface account for 0.23mm². OPD is monolithically integrated over the MicroLED matrix, occupying the interpixel trench area as shown on Figure 1.

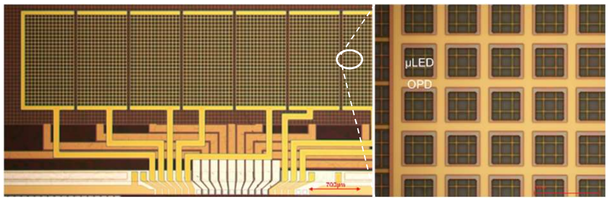

Figure 1 : Device Top view. a) complete Device b) zoom of OPD integrated over MicroLED interpixel trench.

2.2. Challenges of the co-integration

For this co-integration a MicroLED GaN flow on 8'' LED GaN on Si wafers, compatible with micro-electronic common processes and tool has been selected. Upon the multiple photodetector technologies, such as Si-based or III-V-based, the organic photodetector technology is a more straightforward process. Nevertheless, co-integration requires really smooth p-contact surface, without any topography. Challenge for such type of this co-integration are twofold i) a careful planarization of the MicroLED GaN wafer ii) a p-contact deposition roughness compatible with OPD requirement. Besides, with respect to technology co-integration between MicroLEDs and photodetectors, the process flow compatibility remains a real challenge mainly in terms of temperature or bandgap accordance between organic and inorganic materials.

2.3. Description of co-integration strategy

Related to this co-integration, an optimal layout is exploited : the OPD opaque Anode is deposited and patterned in order to keep it only between the pixel, above the interpixel trenches, leading to a surface optimization and a very compact architecture.

Related to the process flow, a Transparent Conductive Oxide (TCO) is deposited to define a p-contact for GaN. Then through a hard mask, GaN etching process is performed to define the matrix layout. A dielectric encapsulation process based on Alumina and Silicon oxide is realized in order to reduce sidewall defects and to guarantee electrical isolation. This encapsulation layer is etched to reach the TCO p-contact and the n-GaN region. Finally, a metallic Al-based contact is deposited and patterned to form the µLED Cathodes and Anodes pads. Figure 2 highlights the cross section of OPD and MicroLED stacking.

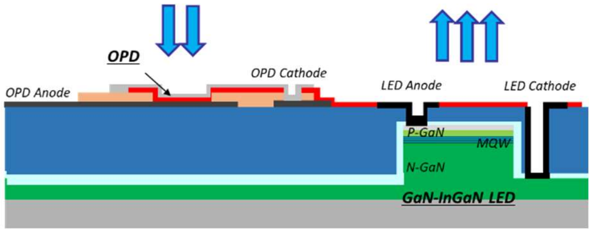

Figure 2 : Device description providing OPD and MicroLED stacking.

As explained in the previous section, before any OPD deposition, the GaN wafer with functional MicroLED need to be planarized. Indeed, the OPD molecules deposition, based on evaporation process, needs a very low roughness and topology to operate. In order to meet these requrements, a silicon oxide CMP is performed to planarize the wafer, right after the GaN MicroLED process. The latter ensure a flat topological surface that allows an Al-based deposition and patterning of the OPD opaque p-contact and the device's pads. A photoresist is spun in order to ensure further OPD n-contact continuity and separate cathode and anodes areas. The OPD based on ZnPc:C60 core material, and its semi-transparent n-contact is deposited with a standard evaporation step through shadow masks on a large dies surface. At last, the OPD is passivated with thin low temperature dielectrics to prevent atmosphere and humidity aging of the molecules.

The overall thickness between the reflective p-contact and the semi-transparent n-contact, forming an optical cavity, is designed in order to enhance the OPD's light absorption for specific wavelength.

3. Measurement results

MicroLED is supposed to provide high radiance that could be beneficial from radiometric budget link perspective between illumination source relying on MicroLED on one side and a photodetector on the other side. Concerning OPD, even if the co-integration with MicroLED is less stringent than with organic material, OPD may suffer from lower performances in terms of dark current in comparison with its silicium counterpart. As a result, photodetector sensitivity could be lower because of excess shot noise due to dark current. The objective of this section is to quantify these assertions relying on co-integrated device measurements. On one hand MicroLED are characterized in terms of radiance and radiation pattern. On the other hand, responsivity and dark current of OPD is provided. At last, cross-talk between MicroLED and OPD is deeply analyzed to give some insight of co-integration trade off.

3.1. MicroLED performances

MircroLED performances are measured on a dedicated experimental setup highlighted on Figure 3. A multi-probe allows to simultaneously characterize all MicroLEDs blocks and OPDs on the device shown Figure 1.

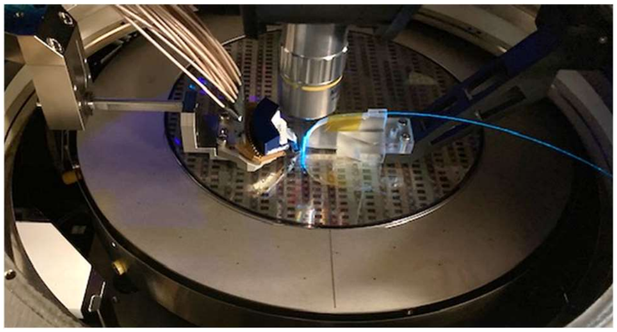

Figure 3 : Experimental setup used to characterize MicroLED and OPD.

An optical fiber located above the MicroLEDs collects a fraction of the emitted light. Based on this fraction of emitted light power in a given solid angle depending on numerical aperture of the fiber, it is possible to infer the overall radiated power knowing the in advance the radiation pattern. Thus, this radiation pattern of radiant intensity is measured as well. It provides the angular distribution of optical power emitted by the MicroLEDs. Results are highlighted on Figure 4 for a single MicroLED. The radiation pattern exhibits a non lambertian emission. An analytical radiation pattern model of the radiant intensity as a function of orientation angle θ shows an evolution proportional to $\cos^n(\theta)$. Figure 4 shows a very good agreement between this analytical model with n = 2,79 and experiment. Relying on these measurements, the overall optical power emitted by a MicroLED block $P_{out,LED}$ is computed and reaches 16 µW.

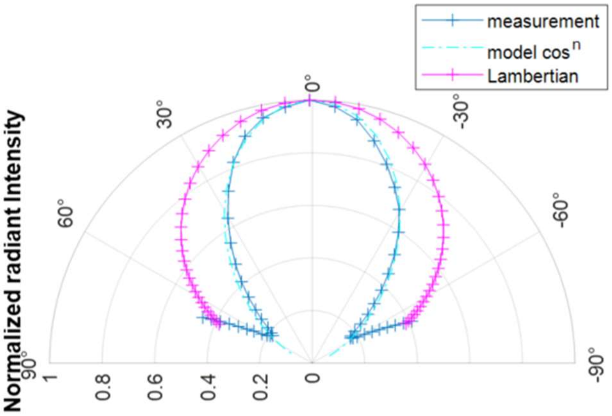

Figure 4 : Radiation pattern of radiant intensity of typical co-integrated µLED

3.2. Co-integrated OPD performances

The responsivity that describes the ability of a photodetector to convert the incident optical power on a photodetector into electrical signals is one of the main relevant characteristic of a photodetector. We setup a measurement to extract OPD responsivity as a function of wavelength on the co-integrated wafer highlighted on Figure 3. To do so, a tunable light source coupled with a monochromator is used to provide light at a given wavelength from 500 nm to 900 nm. The signal is sent to the OPD thanks to an optical fiber located right above the OPD so that the input light area could be considered equal to the fiber core. A sweep in biasing voltage is performed on the photodetector. For each voltage point, all measurements are done simultaneously (incident optical power and wavelength, electrical photocurrent).

Figure 5 shows the responsivity as a function of wavelength. For the co-integrated OPD, responsivity reaches a peak of 0,11 A/W at 600 nm. At this wavelength, it corresponds to a quantum efficiency more than 23% in line with state of the art in the literature (2). On the same graph we compared the results of co-integration with respect to standalone OPD relying on baseline wafer. The baseline wafers are composed of large size-OPD on Al-based anode. Both responsivity are in the same range of magnitude. Unlike the co-integrated version, the standalone one shows a flat behavior up to green light region. Some hypothesis may explain these discrepancies in this region. Indeed, the quality of this anode and the caping layer thickness above the Aluminum on those wafer are different of the one used for the co-integration. Moreover, on the co-integrated wafers, the OPD anode is patterned and a resist is used to ensure cathode continuity. Thus, the optical cavity optimization slightly differs between both versions.

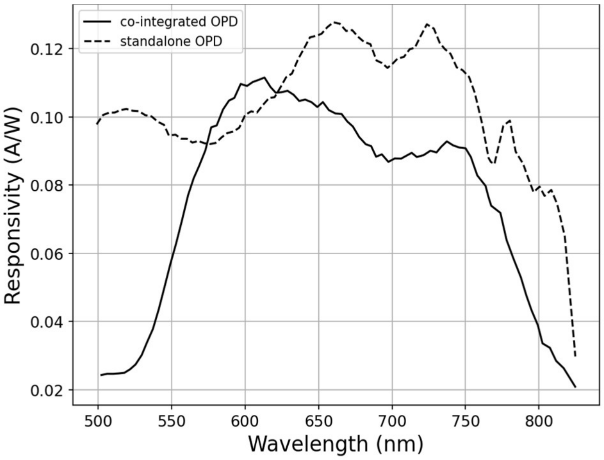

Figure 5 : Responsivity at -1 V as a function of wavelength for co-integrated and standalone OPD.

Figure 6 shows the current density expressed in A/cm² under dark condition of one OPD block. Co-integrated OPD reaches dark current density close to 427 nA/cm^2 at -1 V. Although there is some room of improvement concerning this dark current level, this performance is in agreement of alternative solution in the literature promoting co-integration of illumination source and organic photodetector (12).

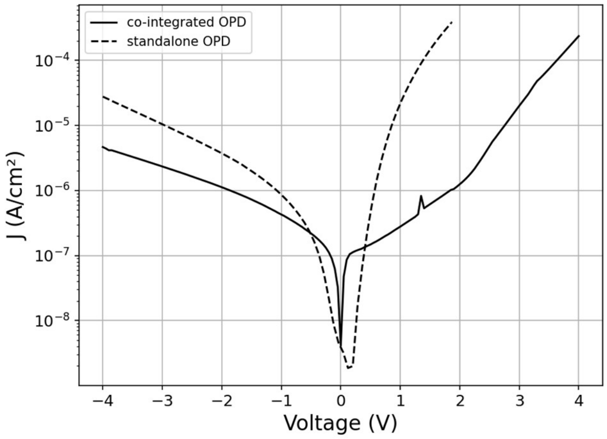

Figure 6 : J,V characteristics and dark current density for co-integrated and standalone OPD.

When considering photodetectors interleaved with MicroLEDs, direct cross-talk between both of them may happen and be responsible for OPD sensitivity alteration and overall system performances degradation. Indeed light coming from MicroLED illumination source may reach directly the photodetector before any informative reflection to the observation scene. In order to characterize the cross-talk, we measure the OPD photocurrent in presence of co-integrated MicroLED source activation located in the same plane. Various distances between OPD and illuminated MicroLED blocks are considered. Figure 7 shows measurement results and the computation of the cross-talk coefficient as a function of MicroLED-OPD distance. The cross-talk coefficient is defined according to equation (1). It stands for the ratio between power delivered by the MicroLED block $P_{out,LED}$ to the power received into the OPD due to the cross-talk $P_{in-XTalk,OPD}$. This latest value is computed based on the difference between the measured photocurrent i_{pd} and dark current i_{dark} divided by the responsivity $\mathcal{R}$ we characterized in the previous section.

$$X_{OPD\ ,LED} = \frac{P_{in-Xtalk,OPD}}{P_{out,LED}} = \frac{i_{pd} - i_{dark}}{P_{out,LED}.\mathcal{R}} \qquad (1)$$

As expected, a strong direct coupling and cross-talk is measured when LED and OPD are superimposed (i.e. a distance of 0 µm). It decreases with distance and is significantly reduced for distance between OPD and MicroLED above 1200 µm.

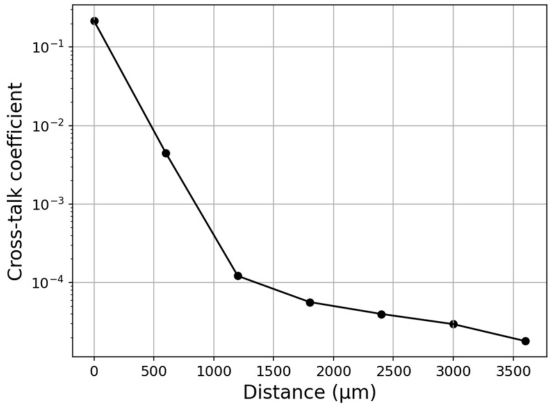

Figure 7 : Optical cross-talk coefficient between OPD and LED illumination source as a function of distance between LED block and OPD block.

4. Conclusion

MicroLED is seen to be a promising technology for next generation of display. Its high brightness offers the unique opportunity to embed sensor within the same plane of MicroLED because of available surface that paves the way of multifunctional display. In this paper, we tackle the co-integration of such MicroLED and specific class of photodetector based on organic material. We demonstrate the capability of MicroLED and OPD co-integration. We deeply analyze the effect of co-integration on OPD performances especially on its responsivity and dark current. Also, we setup a measurement protocol and define a figure of merit to rigorously extract the cross-talk coefficient between MicroLED and OPD. This phenomena remains a bottleneck regarding performances of multifunctional display. Future works are manifold and could cover the improvement of intrinsic performances of MicroLED (radiance) or OPD (dark current) and also cross-talk mitigation technics.

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