Optical issues of OLED displays with a photo sensor for in-pixel optical feedback

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Abstract

Amorphous silicon photo diodes incorporated in a polyLED stack are applied in in-pixel optical feedback to compensate for polyLED degradation. Large quantum efficiencies and perfect linearity are demonstrated. The photosensitivity is in agreement with optical modeling of the stack. A new scheme for ambient and cross talk light cancellation is given.

1. Introduction

A major obstacle for widespread introduction of organic LED (OLED) displays is the degradation of the OLED material. In particular differential degradation will limit the lifetime significantly, since burn-in and color shift may be visible after only 5% OLED device efficiency decrease. An excellent method to compensate for differential OLED degradation as well as for active matrix non-uniformities is by in-pixel optical feedback [1,2]. A photo sensor is incorporated in each pixel, which regulates the pixel luminance to the desired value. Several active matrix pixel circuits enabling optical feedback have been developed. The most promising circuit is one in which the OLED emits a constant luminance level with a duty cycle determined by the pixel data and photo sensor signal [2,3].

In the recent past the use of phototransistors as sensor has been demonstrated [4]. However, these devices are not ideal due to their sensitivity to optical cross talk [5] and due to their low photosensitivity [6]. Here, we discuss in detail the incorporation of an amorphous silicon photo diode and the optical coupling to an OLED. Optical modeling of the light coupling between photo sensor and OLED gives an insight in the sensitivity of the photo current to the OLED device layer stack properties. The good linearity of the photo diodes enables a new external light cancellation circuit, which will be described in the last section.

2. Technology

Devices with amorphous silicon NIP photo diodes were fabricated on glass within the Low Temperature Poly-Silicon (LTPS) process with only one additional mask step. PolyLED material is spin coated on the ITO anode followed by a metal cathode deposition. The anode is connected either passively to an external contact, or to the LTPS active matrix circuit. In the present study we focus on the optical coupling between the OLED and the photo diode of the passive devices. a-Si Photo diode sensors have been commonly used in X-ray image scanners products and have been shown to be completely stable when a reverse bias is applied [7].

3. Efficiency modeling

The coupling of emitted OLED light into the photo diode is key in determining the photosensitivity. This sensitivity can be expressed as generated photo current per luminance viewed by the display viewer. To model the emitted light, we used the equivalence between the radiation pattern of an electrical dipole antenna and the probability for the emission of a photon by a dipole transition, as put forward by K. Neyts [8]. This model takes into account the interferences due to reflections at interfaces in the specific stack and the absorption in these layers. The result is an angular distribution of the relative emitted intensity per wavelength, which is multiplied by the nominal emission spectrum of the polymer.

The photo current is determined by the absorbed intensity of light in the a-Si layer of the photo diode. This intensity is denoted by $A(\theta,\lambda)$, and indicated in Figure 1. The absorbed intensity is then expressed as a number of photons by multiplying with λ/hc. The photo current is obtained by multiplying with the device quantum efficiency (QE, in electrons per photons) times the electron charge e and integration over the wavelength and solid angle:

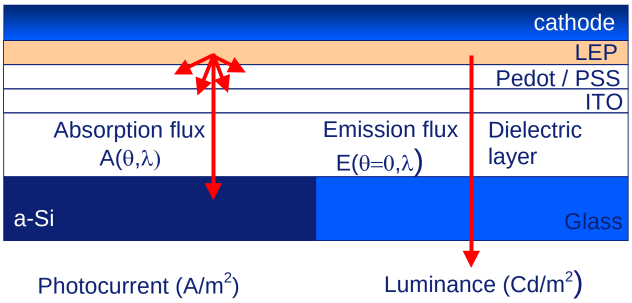

Figure 1. Schematic diagram of the stack, with light absorption in the photo device (left) and emission towards the viewer (right).

$$J_{photo} = \frac{e}{hc} \int_{\lambda} \int_{\Omega} QE(\lambda) \cdot \lambda \cdot A(\theta,\lambda) d\Omega d\lambda$$

The QE can be determined from stand-alone devices using an external calibrated light source.

The observed luminance by a viewer in front of the display is found by multiplying the forwardly emitted intensity *(E(θ,λ))* per area with the eye sensitivity curve *V(λ)* and integration over all wavelengths:

$$L_v = \left(\int_{\lambda} V(\lambda) \cdot E(\lambda, \theta = 0) d\lambda\right) / dA$$

The device photosensitivity is then given by:

$$\eta_{photodevice} = J_{photo} / L_v$$

and is expressed in A/Cd. This is a convenient quantity as it relates the device photo current to the perceived luminance.

Using the stack configuration and layer thicknesses of our fabricated devices, the calculated sensitivities for R, G, and B are 0.0068, 0.0037, and 0.0109 A/Cd respectively. The relatively low sensitivity in the green is explained by the lower number of photons in one Candela in the green (a consequence of the eye sensitivity). The thickness dependent interferences in the stack are different for the absorption flux and emission flux. The photosensitivity therefore depends on these layer thicknesses and non-uniform layers may cause a non-uniform feedback across the display. The stack modeling is a powerful capability in optimizing the stack to reduce non-uniformity influences. The polyLED layer thickness must be optimized for maximum emission towards viewer. The optimal thickness depends on the polymer material and is in the order of 50-80 nm.

The detector senses light emitted at a wide range of angles including angles that cannot be coupled out of the glass, and therefore receives more light (per area) than the viewer. The ratio of light coupling into the detector and into air is determined by the emission profile, which besides layer thickness influences, depends on the precise position of the dipole emission. Assuming an average dipole distribution, we found that the radiant incidence on the detector is a factor of ~2 higher than the radiant exitance towards the viewer.

4. Optical coupling measurements

The results of quantum efficiency measurements of the standalone NIP diodes with different sizes are presented in Figure 2. With a calibrated external light source and the use of color filters, the photo current was measured at several wavelengths. A large quantum efficiency (above 0.5) is found for the polyLED emission peaks of 470 nm (blue), 550 nm (green), and 620 nm (red). The photo diode shows a superior sensitivity compared with alternatives such as a phototransistor.

The measured photo current as a function of light emission from the polyLED layer on top of the diode is indicated in Figure 3. An excellent linear relationship is found for a light intensity increase of more than 4 orders of magnitude. This linearity assures that the degradation of the light output is monitored by this photo sensor with high accuracy. It also shows that the ratio of light coupled into the photo diode and light coupled out into air is constant and independent of the generated light intensity.

The photo diodes have dark currents below 1 pA in the operating range, which is more than an order of magnitude lower than the photo current at low light intensity.

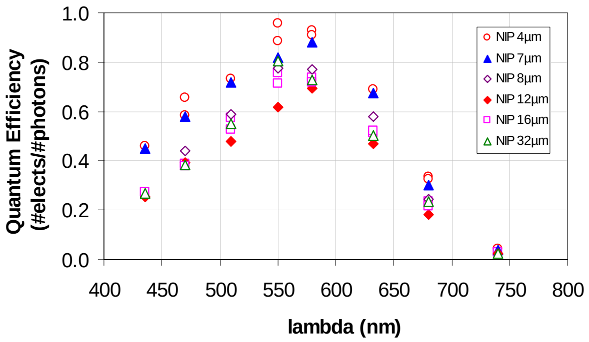

Figure 2. Quantum efficiency of standalone photodiodes.

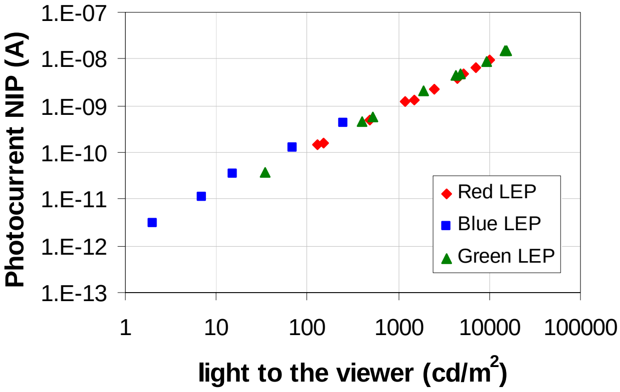

Figure 3. Photo current of the NIP photodiode underneath a red, green, and blue polymer.

The sensitivity of the photo diodes is obtained by determining the photo current and the broadband emitted light from the polyLED simultaneously. It is practically independent of the polyLED luminance. In Figure 4 the experimental results for the three colors are given and compared with the modeling. We find a very good agreement between the modeling and measured results. The agreement indicates that the model very well describes the coupling of the emitted polyLED light into the NIP stack. The model can thus be used to investigate the influence of layer stack properties on the photo sensor sensitivity.

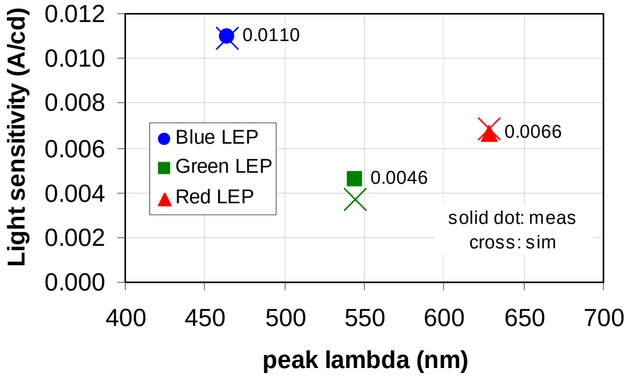

Figure 4. Sensitivity of the NIP photo diodes underneath the red, green, and blue polyLED stack.

5. External light cancellation

An important requirement for optical feedback is that the in-pixel photo diode only senses light from the OLED of that particular pixel. Other light sources will degrade the performance of such schemes. To ensure this we present a novel differential light cancellation scheme, see Figure 5. External light is allowed to fall upon both photo diodes so that the generated photo current passes directly through the two diodes and does not charge the capacitor. The OLED light that we wish to sense falls upon only one of the diodes, therefore the generated photo current charges the capacitor and we are able to sense this light source only.

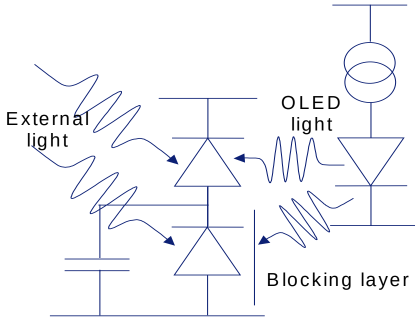

Figure 5. Differential light cancellation scheme.

For optimal functioning the percentage current change per volt ($\Lambda = (\Delta I/I)/\Delta V$) of the photo diode must be low (i.e. it must have a very high output impedance). Otherwise the photo current generated by external light will depend upon on the applied bias across each diode and unwanted charging of the capacitor occurs. In Figure 6, Λ is given for reverse bias voltages between 5 to 10 V taken at typical light levels relevant for the operation of the pixel circuit as described in [2]. In general we find that Λ is of the order of 1% per volt enabling external light sources to be rejected very effectively.

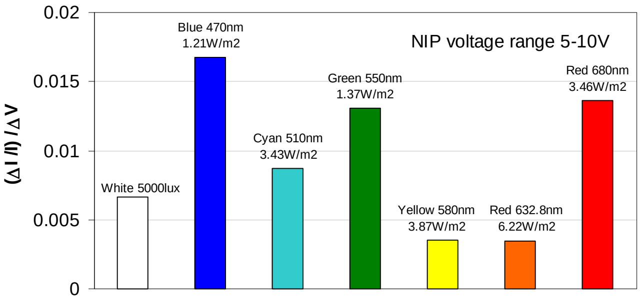

Figure 6. Bias voltage dependence of the photo diode for several wavelengths.

In Figure 7 the resulting operation of this circuit is demonstrated for two data values with and without external light on the pixel. The complete pixel circuit is similar to the improved optical feedback pixel circuit described in [2]. The OLED drive voltage shows a rapid return to zero when the photo diode current fully discharges the data storage capacitor. The time integrated luminance is weakly influenced by the 8000 Lux external light: only 10% less light is emitted. The circuit is thus capable of almost eliminating the ambient light influence on optical feedback.

Here we showed the light cancellation circuit operation for bottom emission OLED where the photo sensor faces the OLED on one side, and external light on the other. This approach is also very suitable for top emission OLED displays, where the photo sensor faces both OLED and external light on one side. In this configuration shielding the photo sensor from the external light is not possible, and external light cancellation is clearly necessary.

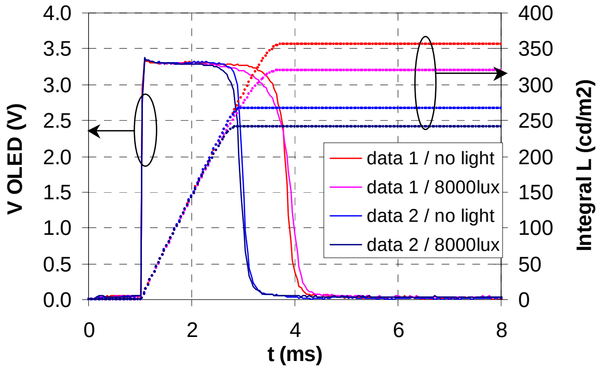

Figure 7. Influence of external light on the OLED drive voltage and integrated luminance in the light cancellation pixel circuit.

6. Conclusions

Optical feedback is a very attractive method to counter differential degradation of polyLED displays and correct for active matrix non-uniformities. A crucial part of all optical feedback schemes is the light coupling between photo sensor and OLED. Understanding of this coupling is achieved by optical modeling of the stack. We showed that the modeling is in excellent agreement with experimental results using a-Si photo diodes. We demonstrated a novel technique for external light cancellation using an additional photo sensor and utilizing the very high output impedance of the photo devices.

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