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Quantitative analysis of pixel crosstalk in AMOLED displays

Matthias Diethelm^{a,b,c}, Lieven Penninck^a, Stéphane Altazin^a, Roman Hiestand^a, Christoph Kirsch^b and Beat Ruhstaller^{a,b}

^aFluxim AG, Winterthur, Switzerland; ^bZurich University of Applied Sciences, Institute of Computational Physics, Winterthur, Switzerland;

^cLaboratory for Functional Polymers, Empa, Swiss Federal Institute for Materials Science and Technology, Dübendorf, Switzerland

ABSTRACT

The resolution of organic light-emitting diode (OLED) displays is increasing steadily as these displays are adopted for mobile and virtual reality (VR) devices. This leads to a stronger pixel crosstalk effect, where the neighbors of active pixels unintentionally emit light due to a lateral electric current between the pixels. Recently, the crosstalk was quantified by measuring the current flowing through the common hole transport layer between the neighboring pixels and comparing it to the current through the active pixel diode [S.-K. Kwon, K.-S. Kim, H.-C. Choi and J. H. Kwon, presented at the International Meeting on Information Display, Jeju, South Korea, 2016]. The measurements showed that the crosstalk is more crucial for low light levels. In such cases, the intended and parasitic currents are similar. The simulations performed in this study validated these measurement results. By simulations, we quantify the crosstalk current through the diode. The luminous intensity can be calculated with the measured current efficiency of the diodes. For low light levels, the unintended luminance can reach up to 40% of the intended luminance. The luminance due to pixel crosstalk is perceivable by humans. This effect should be considered for OLED displays with resolutions higher than 300 PPI.

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OLED; display; crosstalk; simulation; Laoss

1. Introduction

The organic light-emitting diode (OLED) display technology is used in smartphones around the world as well as in virtual reality (VR) applications. It is a common practice to try to reduce the complexity of OLED display fabrication using non-patterned common layers in the OLED stack [1,2]. That is, besides the common cathode, the hole transport layer (HTL) is also deposited uniformly onto the patterned anode, as shown in Figure 1(b). In Figure 1(a), a typical RGB pixel pattern with roughly 300 PPI is shown, but the crosstalk effect also appears in the other pixel patterns. One issue of this approach is the crosstalk effect, where pixels other than the active ones emit unintended light. This effect occurs because an electric current flows from the active anode via the highly resistive common layer through the neighboring pixels to the common cathode (see Figure 1(c)).

Crosstalk effects have already been studied in the past [3,4], and solutions have been found, which meet the OLED display industry standards. For instance, a finite pixel separation distance prevents this effect from having a significant influence on the visible performance.

Modern displays with pixel densities of 300 PPI or higher, however, may again suffer from the crosstalk effect because for similar brightness requirements, the pixels must be located closer to one another, which leads to reduced resistance between them [1]. Recent studies have shown very high pixel densities of above 1000 PPI without any crosstalk effect for high voltages, but for low voltages and thus for low light levels, there is a visible crosstalk effect [5]. Measuring the crosstalk current is not an easy task because in a typical OLED display structure, a common cathode is used. Therefore, it is not possible to directly measure the current through the inactive pixels. In a recent study, the crosstalk effect was characterized by measuring the current between the anodes of an active pixel and an inactive pixel, thus allowing the assessment of the lateral conductivity between the pixels [6]. This current was then taken as a measure for the crosstalk current that would flow through the inactive pixel diode to the cathode if the anodes were not probed. Only numerical modeling of the crosstalk effect allows the determination of the current through the inactive pixel, which cannot be determined experimentally whereas the lateral

CONTACT Lieven Penninck  lieven.penninck@fluxim.com  Fluxim AG, Technoparkstrasse 2, 8406 Winterthur, Switzerland

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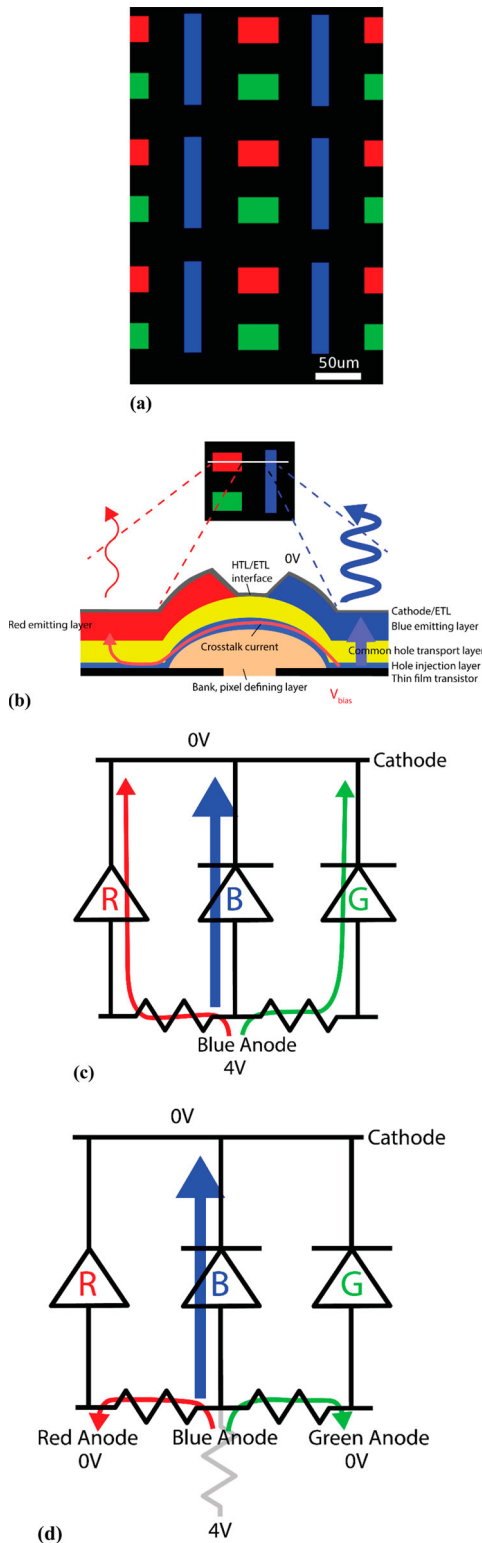


Figure 1. Side-by-side pixel layout (a) of the produced RGB OLED display. The pixels share common hole transport and injection layers, which leads to a crosstalk current (b). In this normal operation mode, the crosstalk current flows through the common-layer resistance and the diode (c). If the anodes of the neighboring pixels are connected to the ground, then the current flows only through the common-layer resistance (alternative operation mode) (d). The gray resistance represents the series resistance of the device.

conductivity is accessible experimentally and provides an important input for simulation.

The large-area semiconductor device simulation software Laoss by Fluxim AG [7] was used in this study to investigate the crosstalk. The Laoss software solves the current continuity equation in a top 2D domain and a bottom 2D domain through the finite-element method (FEM). The two 2D domains are coupled by a vertical coupling law described by three current density vs. voltage curves for the red (R), green (G), and blue (B) pixels. The common cathode in the top domain is a single large-area electrode whereas the patterned anodes in the bottom domain are smaller. The simulation shown below assumed the (anode) pixel pattern shown in Figure 3, which is consistent with the pixel pattern shown in Figure 1(a).

2. Methods

2.1. Experiments with AMOLED pixels

The experimental data and inspiration for the present study were taken from a contribution by Kwon et al. [6], who fabricated AMOLEDs with a side-by-side RGB structure, as shown in Figure 1(a). The different pixels have common hole injection and transport layers, as shown in the cross-section in Figure 1(b). If only one pixel is switched on and the neighboring pixels are not, a crosstalk current flows from the anode of the active pixel to the cathode, first laterally along the common layers and then through the neighboring pixel diode. The resistance to this flow is high due to the very thin pixel-defining layer, such that very low crosstalk currents are observed. The schematic of this so-called ‘normal operation mode’ is shown in Figure 1(c). To quantify and measure the crosstalk current, the anodes of the neighboring (inactive) pixels were probed to collect the current, as shown in Figure 1(d). In the normal operation mode, as shown schematically in Figure 1(c), the crosstalk current runs through the diode, making it impossible to measure it because the cathode is connected to all the pixels simultaneously. In the *alternative* operation mode shown in Figure 1(d), on the other hand, the crosstalk current can be measured through the respective anodes. Note that this current is an upper limit of the current through the diode in the normal operation mode; that is, the current through a series connection of the common HTL and the neighboring diode will be lower than the current through the common HTL alone for the same applied voltage. This is because in this serial connection, the applied voltage is split between the diode and the resistance.

The currents at the blue, green, and red anodes and at the cathode were measured while sweeping the voltage

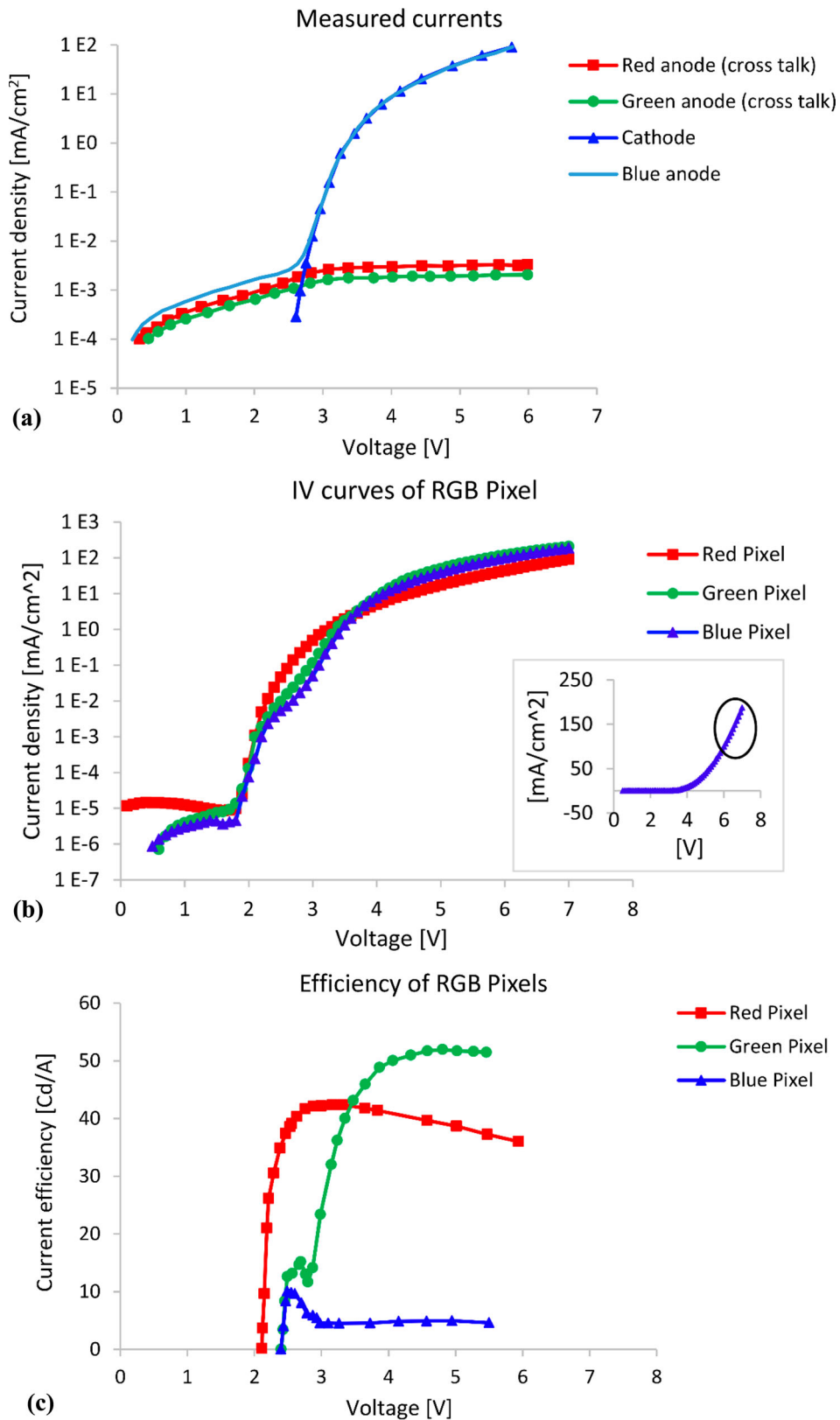


Figure 2. Measurement of the (crosstalk) current through the red and green pixels (a). The electric current through the anode of the active blue pixel is the sum of all the other currents. The JV curves of the red, green, and blue pixels were measured (b). They are imported into the Laoss simulation software as local JV curves. The inset figure shows the blue diode curve on a linear scale, from which the series resistance of the blue diode is extracted at high voltages. The measured current efficiency for each pixel color is used to convert electric current into luminance (c).

from 0 to 6 V at the blue anode, as shown in Figure 2(a). The measured green and red anodes were crosstalk currents, as described above, and the measured cathode was the active current through the diode. The current measured at the blue anode was the sum of all the three currents and therefore did not reveal additional information for the quantification of the crosstalk effect. The saturation behavior of the red and green currents above 3 V presumably resulted from the series resistance of the device, as shown in Figure 1(d). It was extracted from the slope of the measured IV curve (device area: 0.25 cm^2) of the blue OLED in the region shown in Figure 2(b), and was about 60Ω . For higher applied voltages and thus currents, the voltage drop across the series resistance increased, such that the voltage across the diode and the common-layer resistance was saturated. The simulation of the observed current saturation is discussed and explained further in the supplemental information, where the non-linear region below 3 V is also discussed. Figure 2(b) shows the current density–voltage (JV) relation for each pixel color, which was measured by biasing all the anodes of the same color without probing the neighboring color anodes, as in Figure 1(c). These data were imported into the Laoss software as a coupling law between the top and bottom electrodes for each pixel color. While the crosstalk effect was due to the current, its impact on the visible display color was relevant. The luminance (corresponding to the current through each pixel) was calculated to compare the intentional emission to the parasitic emission. The luminous current efficiency of each pixel color was measured, as shown in Figure 2(c). Using this data, the current in amperes was converted to

luminous intensity in candela. This photometric quantity included the human perception.

2.2. Modeling approach

The pixel layout was drawn in a CAD tool and then imported into Laoss using the DXF format. The triangular simulation mesh had an edge length of $5 \mu\text{m}$, which resulted in 8000 vertices for the structure shown in Figure 3. The size of the finite elements was chosen so that a further reduction of the mesh size would not yield a noticeable difference in the simulation results.

The region between the pixels (the black region in Figure 1(a)) is expected to have very high resistivity between the bottom and top electrodes (yellow HTL/gray ETL interface in Figure 1(b)). This is because the electron-blocking HTL and the hole-blocking electron transport layer (ETL) are directly connected to each other (there is no emissive layer in that region). Therefore, the holes and electrons cannot combine effectively so that the current is very low and the resistivity is very high [8]. For simplicity, the resistivity in that region was assumed to be infinite in the simulation performed in this study (i.e. zero conductivity between the top and bottom electrode domains). The top electrode of a color pixel is expected to have the sheet resistance of a typical transparent conductive electrode (TCE) whereas its bottom electrode is more metal-like. In this study, 20 and $2 \Omega/\text{square}$ were used, respectively. The sheet resistance between the pixels (the black region in Figure 1(a)) in the top electrode is again expected to be TCE-like whereas the relevant sheet resistance for the lateral current in the

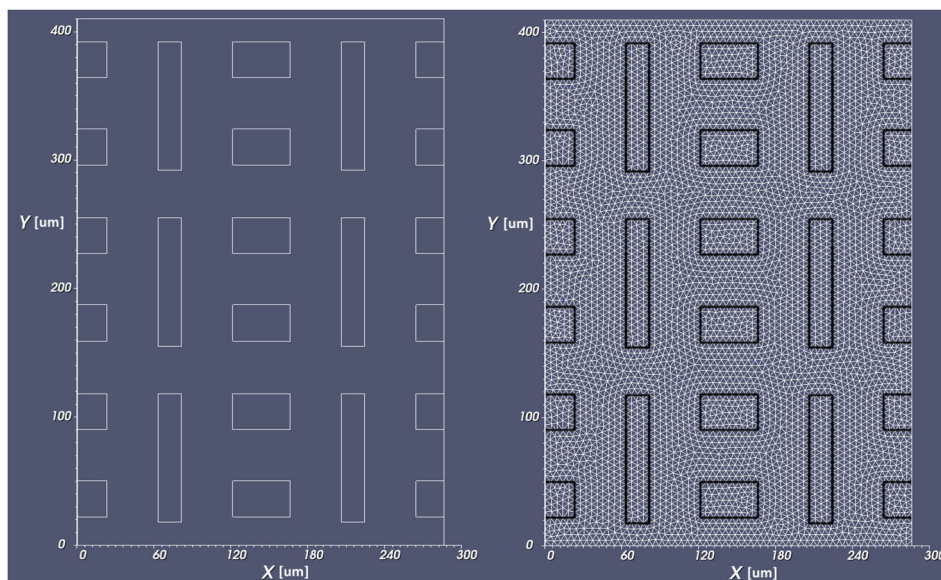


Figure 3. Laoss pixel array geometry and finite-element mesh.

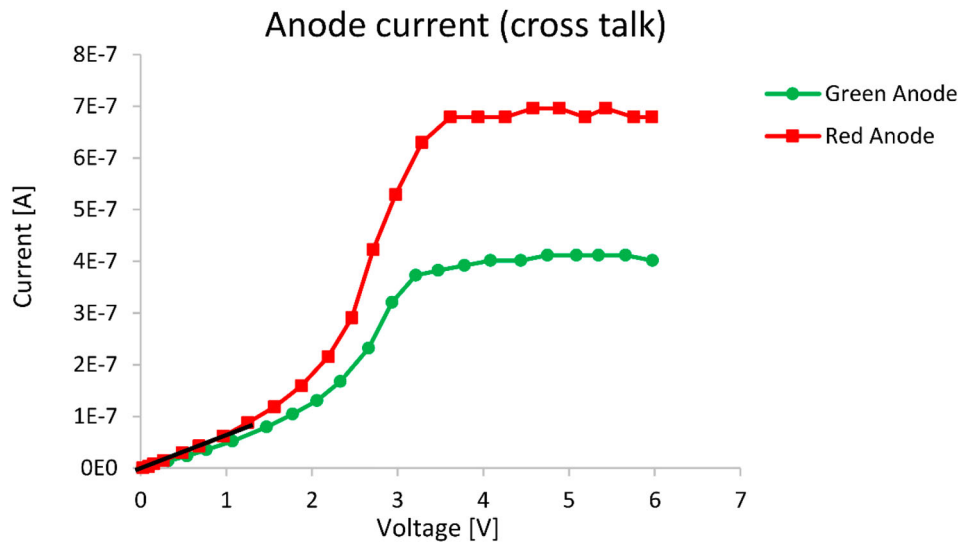


Figure 4. Linear plot of the crosstalk current. Below 2 V, the current-voltage relation is linear due to the transport across only the common layer. Its resistance can be extracted from the slope of the current-voltage curve ($R = U/I$), as marked by the black line.

Table 1. Sheet resistances for the different electrode regions used in the simulation.

Electrode	Sheet resistance $[\Omega/\square]$
Top electrode pixel & intermediate region (TCE)	20
Bottom electrode pixel (HTL/metal)	2
Bottom electrode intermediate region (common layer, crosstalk resistance)	120e9

bottom electrode was extracted from the measurement, as shown in Figure 4.

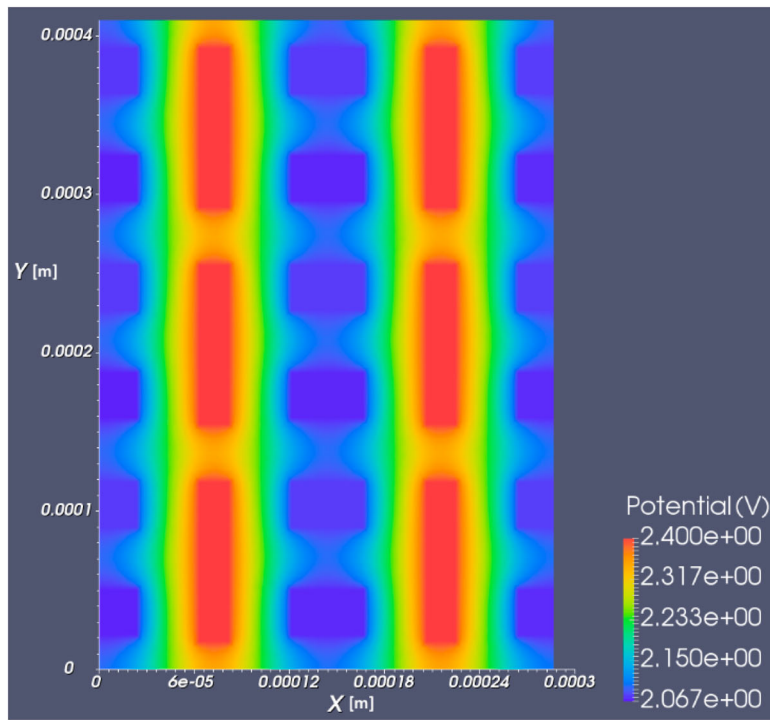
The aforementioned is the same measurement as that in Figure 2(a) but plotted with a linear scale on the vertical axis and with the current instead of the current density. For voltages lower than 2 V, the (Ohmic) current flows only through the common layer, and all the non-linear elements (diodes) are still in the blocking condition so that only a linear effect is observed. Therefore, the crosstalk resistance can be extracted from the slope of the linear region (as marked with the black line in Figure 4), which yields $15.5 \text{ M}\Omega$. To obtain the final input resistance, such value is multiplied by the number of pixels because the current measurement was done across all the common-layer resistances connected in parallel. The material parameters used as inputs for the simulation are summarized in Table 1.

3. Results and discussion

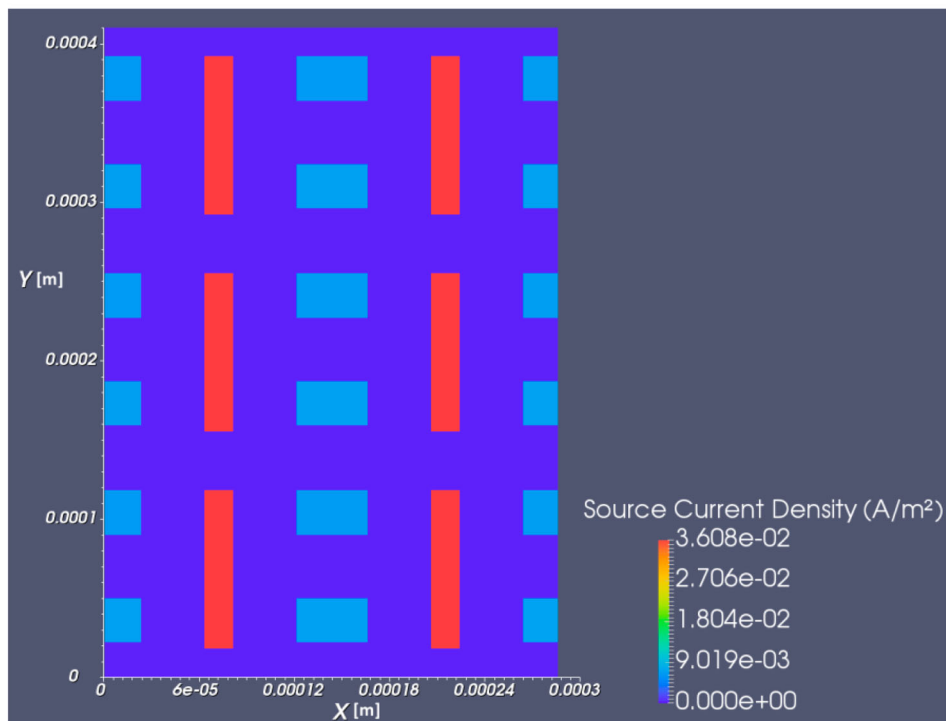
The simulation in this study was done for the normal operation mode, as shown in Figure 1(c), which illustrates the relevant crosstalk effect. The voltage sweep was applied at the bottom electrodes (anodes) of the center blue pixels, and the potential was set to 0 V in the entire

top electrode (cathode). The green and red anodes were not biased. The voltage was varied from 0 to 6 V in 0.2 V steps. Figure 5 shows the potential distribution (a) along the bottom electrode and the current density (b) through the pixel diodes for an applied voltage of 2.4 V at the blue pixel. The crosstalk effect was visible through the current flowing through the inactive green and red pixel diodes, which led to unintentional light emission.

To quantify the crosstalk effect, the currents through the active center blue pixel were compared to one neighboring red pixel and one green neighboring pixel, as shown in Figure 6(a). The simulated JV curves in Figure 6(b) can be compared to the measured values in Figure 2(a). For voltages above 3–4 V, the situation looks very similar, but for lower voltages, it seems different. This is because the measurement is not influenced by the neighboring blocked diodes (both their nodes are at 0 V). In the simulation, however, the current was flowing through the common-layer resistance and also through the diode, which was like a diode with a huge series resistance. Therefore, the crosstalk current followed the diode behavior, whose measured value is shown in Figure 2(b), where similar features can be observed. The measured crosstalk value in Figure 2(a), on the other hand, does not show similarities to the measured diode curves. These differences especially at the low voltages are the reason that simulation was necessary, to get the full picture of the crosstalk. The simulation clearly showed the same trend as the measurement, which was that the pixel crosstalk issue is more severe for low light levels because in such cases, the parasitic current through the neighboring pixels is more similar to the intentional current through the active center pixel. This means that the actual emission



(a)

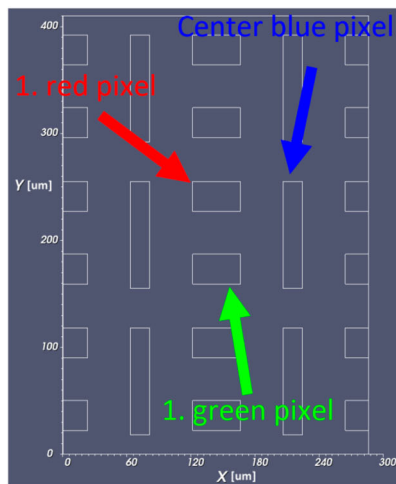


(b)

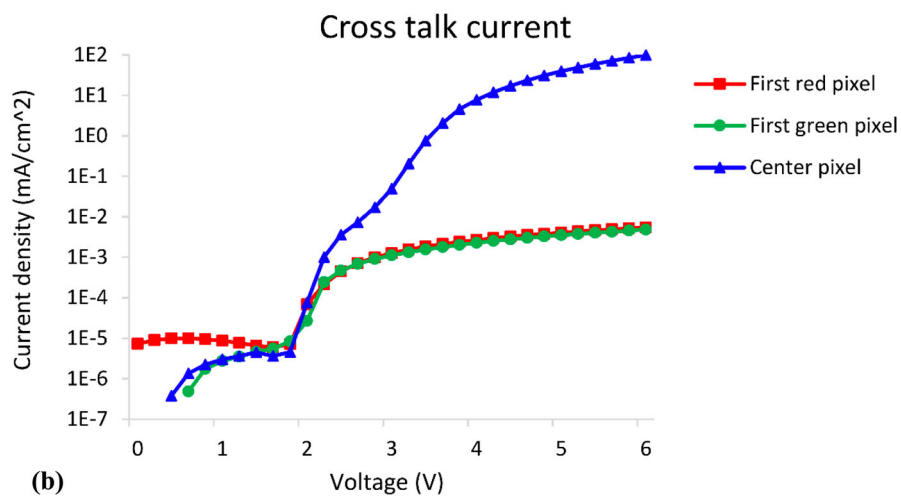
Figure 5. Electric potential (a) and current through the diode (b). The applied voltage at the blue pixel anodes is 2.4 V. At this voltage, the currents through the diode of the inactive green and red pixels are 13% of the current through the active blue pixel.

from the neighboring inactive pixels has a higher impact on the overall display color for low light levels. That is, at low light levels, the color gamut of the display is

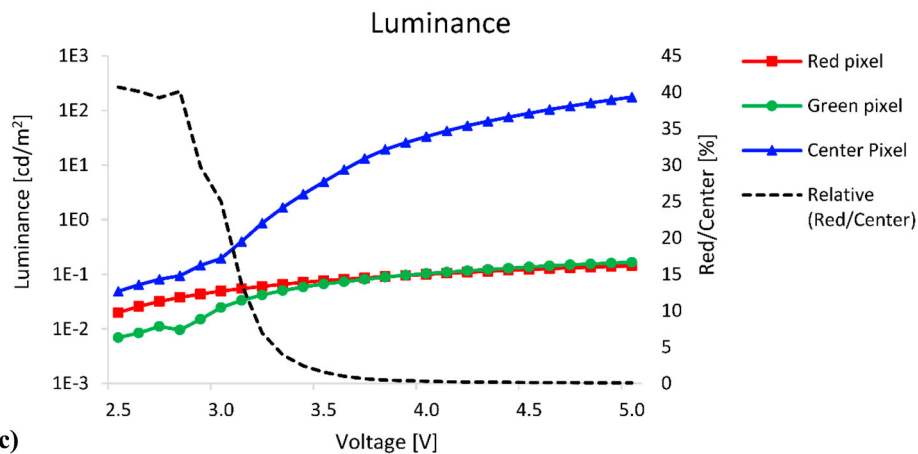
significantly hampered due to the unintentional color mixing caused by the pixel crosstalk. In this study, as the current efficiency was measured for different voltages, the



(a)



(b)



(c)

Figure 6. Compared pixels (a). Simulated currents through the active blue center pixel and through the neighboring red and green inactive pixels (b). Luminance vs. voltage (c). The black dashed line shows the relative luminous intensity of the red pixel with respect to the center (blue) pixel. This ratio quantifies the crosstalk effect.

luminance, which is shown in Figure 6(c), was calculated by multiplying the simulated current through the red, green, and blue diodes by the luminous current efficiency (Figure 2(c)) to obtain the luminous intensity in candela.

The luminous intensity divided by the area of the respective pixel results in the luminance (unit cd/m^2). The black dotted line shows the ratio between the red pixel crosstalk current and the active blue center pixel current. This ratio

serves to quantify the crosstalk effect. For low light levels, the effect is more crucial because the ratio of parasitic to intentional luminance is at its highest. OLED displays reach luminance values in the order of at least 100 cd/m^2 , which agrees with the simulation result of the blue active pixel emission.

The human eye sensitivity to the color of an OLED display can be below 0.01 cd/m^2 [9]. The crosstalk luminance in the simulation reaches 0.07 cd/m^2 for low light levels and can, therefore, have a detrimental effect on the overall color perception of images with low light levels.

Kwon et al. showed the influence of the crosstalk current on the emitted color by varying the doping level of the HTL [6]: the higher the doping level is, the lower the common-layer resistance and thus the higher the crosstalk current. For a low blue intensity, they showed that a crosstalk effect could be observed with lateral current densities above the 0.001 mA/cm^2 level. The blue color slightly shifts to purple, which reveals the presence of parasitic red emission.

4. Conclusion

The crosstalk effect in active-matrix organic light-emitting diode (AMOLED) displays was quantified by measuring the current through the common hole transport layer from the active to the neighboring pixel and comparing it to the current through the active pixel diode. The measurements showed that the crosstalk effect is more pronounced for low light levels because in such cases, the intentional and parasitic currents are similar in magnitude. The simulation results presented in this publication demonstrate the same effect as the measurements and thus reinforce the experimental conclusion. As the simulation yielded values for the crosstalk current through the neighboring diode, the luminous intensity was calculated using the measured current efficiency of the pixels. The relative luminance between the inactive and active pixels is up to 40% according to the results of simulation performed in this study. As this crosstalk luminance is significantly higher than what humans can perceive, the crosstalk effect will lead to a noticeable decrease in performance for OLED displays with pixel densities higher than 300 PPI.

The presented simulation method is useful for pixel layout optimization as well as for the selection of common-layer materials with suitable lateral conductivity.

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Notes on contributors



Matthias Diethelm received his Bachelor and Master of Science degrees in electrical engineering and information technology from the Swiss Federal Institute of Technology in Zurich, Switzerland in 2013 and 2015, respectively. After graduation, he worked as an R&D engineer in the field of organic lighting and photovoltaics measurement and simulation at Fluxim and the Institute of Computational Physics (Zurich University of Applied Sciences). In 2017, he joined the Swiss Federal Laboratories for Materials Science and Technology to write his Ph.D. dissertation on transient phenomena in organic optoelectronic devices.



Dr. Lieven Penninck (M) received his Ph.D. on the optical modeling of anisotropy in OLEDs and liquid crystal devices from the University of Ghent (BR) in 2013. He worked at TPVision (B) in 2013 as a display system expert before joining Fluxim in 2014 as a technical consultant, which put him in close contact with international OLED companies and academics. At Fluxim, he coaches and trains customers/prospects/distributors and is involved in several R&D projects.



Dr. Stéphane Altazin (M) obtained his Ph.D. on the modeling of organic semiconductor devices from CEA-LITEN in Grenoble (FR) in 2011. He joined Fluxim in 2012 as a technical consultant and product manager of the simulation software SETFOS. He has coached for several internal and external R&D projects and services on both the optical and electrical characterization of OLEDs or solar cells.



Roman Hiestand was born in 1971 in Grenchen, Switzerland. He obtained a Master's degree in computer science at ETH Zürich in 1997 and worked mostly in the banking sector until he joined Fluxim in 2015 as a senior application engineer. He is the lead developer of the Laoss large-area organic semiconductor simulation software.



Christoph Kirsch specializes in applied mathematics. He obtained his Master's degree from ETH Zurich in 2001, and his Ph.D. from the University of Basel in 2005. He has used mathematical methods and has developed numerical simulation tools in various fields, such as plasma physics, thermal process engineering, and organic photovoltaics, during his postdoctoral stays in France, Germany, and USA. Since 2012, he has worked as a research associate in the Organic Electronics and Photovoltaics group at the Institute of Computational Physics of the Zurich University of Applied Sciences in Winterthur, Switzerland.



Prof. Dr Beat Ruhstaller is a lecturer at the Zurich University of Applied Sciences ZHAW and the founder of Fluxim. After earning a diploma in physics from ETH Zürich, he obtained his Ph.D. in physics at the University of California, Santa Cruz (USA) in 2000. He was a postdoc at the IBM Zurich Research Laboratory in the display technology group before joining ZHAW, where he headed the Institute of Computational Physics from 2007 to 2010. In 2006, he founded Fluxim, which he has managed as CEO since 2011. Fluxim has successfully brought R&D tool innovations from the lab to the OLED display and lighting as well as solar cell industry.

ORCID

Beat Ruhstaller  <http://orcid.org/0000-0001-5649-8408>

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