AUTHOR QUERY FORM

ELSEVIER	Journal: ORGELE Article Number: 2245	Please e-mail or fax your responses and any corrections to: E-mail: corrections.esch@elsevier.sps.co.in Fax: +31 2048 52799
--	---	---

Dear Author,

Please check your proof carefully and mark all corrections at the appropriate place in the proof (e.g., by using on-screen annotation in the PDF file) or compile them in a separate list. Note: if you opt to annotate the file with software other than Adobe Reader then please also highlight the appropriate place in the PDF file. To ensure fast publication of your paper please return your corrections within 48 hours.

For correction or revision of any artwork, please consult <http://www.elsevier.com/artworkinstructions>.

Any queries or remarks that have arisen during the processing of your manuscript are listed below and highlighted by flags in the proof. Click on the 'Q' link to go to the location in the proof.

Location in article	Query / Remark: click on the Q link to go Please insert your reply or correction at the corresponding line in the proof
<u>Q1</u>	Please confirm that given names and surnames have been identified correctly.
<u>Q2</u>	Please check the telephone number of the corresponding author, and amend if necessary.
<u>Q3</u>	Please provide caption for supplementary material.
	<div data-bbox="400 1805 963 1904"> <p>Please check this box if you have no corrections to make to the PDF file</p> <input data-bbox="851 1819 920 1878" type="checkbox"/> </div>

Thank you for your assistance.

Graphical abstract

Optical determination of the junction temperature of OLEDs

pp xxx-xxx

Jan Buytaert, Johan Bleumers, Alexander Steen, Peter Hanselaer *

Highlights

- A full-field optical method for OLED junction temperature determination is proposed.
- A model of local luminance versus local temperature is developed.
- The method is validated with infrared thermography.
- The self-heating of a commercial OLED at the active organic layer is measured.

Contents lists available at ScienceDirect

Organic Electronics

journal homepage: www.elsevier.com/locate/orgel

Optical determination of the junction temperature of OLEDs

Jan Buytaert^{a,c}, Johan Bleumers^a, Alexander Steen^a, Peter Hanselaer^{a,b,*}^a Light & Lighting Laboratory, KaHo Sint-Lieven, Ghent, Belgium^b ESAT/ELECTA, KU Leuven, Belgium^c Laboratory of BioMedical Physics, University of Antwerp, Belgium

ARTICLE INFO

Article history:

Received 22 May 2013

Received in revised form 15 July 2013

Accepted 27 July 2013

Available online xxxx

Keywords:

OLED

Junction temperature

Luminance

Optical measurement

ABSTRACT

This paper describes a novel optical measurement technique for the *in situ* determination of the spatial temperature distribution at the organic layer level in large-area organic light-emitting diodes (OLEDs). The local junction temperature of OLEDs is a very important factor with respect to the luminance uniformity. Moreover the variation of local temperatures leads to a non-uniform depreciation of its light output, which in turn increases the luminance non-uniformity over time and affects the lifetime expectancy of the OLED.

Junction temperature maps can be derived from easily measurable luminance maps after a dedicated calibration procedure. The underlying model based on the relationship between the local diode electrical behavior and the light emission at different temperatures. The method is illustrated for the self-heating of a commercially available OLED for lighting, and validated by comparison with infrared thermography.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Organic light emitting diodes (OLEDs) are used in displays for several years now, but OLED technology is also a promising technology for general lighting applications [1], offering numerous advantages over other light sources. Even compared to LEDs, they can be made thinner, lighter and more flexible, and their surface area is much larger. Furthermore, both LED and OLED have low power consumption.

The main remaining obstacles for OLED technology are the moderate system efficiency and luminous flux, the lifetime, the uniformity and the price. The main optical and electrical characteristics are strongly dependent on the local diode junction temperature.

In order to have a perfect uniform emitting OLED, one would need a constant local diode behavior, a constant voltage as well as a constant temperature over the whole surface, which is impossible to achieve. While voltage

non-uniformity can be strongly improved by adding metallic conducting grids on top of the typically transparent conductive oxide (TCO) thin film surface electrodes – often indium tin oxide (ITO) [2] – a certain amount of self-heating will always be produced. When heat is dissipated more efficiently at one position on the surface than at another (for instance the OLED edge versus its center), a temperature distribution will arise, causing unwanted luminance non-uniformity. Furthermore, high temperature values of the emitting organic layers will strongly diminish the overall device lifetime expectancy [1,3–5]. What is more, strong temperature differences over the surface could also cause locally accelerated aging, leading to increasing luminance non-uniformity over time [4].

For the reasons mentioned above, it is clear that the junction temperature distribution is a critical OLED application parameter and that it is crucial to monitor the temperature distribution over the entire surface. However, due to the encapsulation, direct junction temperature determination of the organic layers is not possible.

Infrared thermography (IRT) is a possible technique that has been successfully applied to study OLED heating behavior [4]. However, its results correspond to the

* Corresponding author. Address: Light & Lighting Laboratory, KAHO Sint-Lieven, Gebroeders De Smetstraat 1, 9000 Ghent, Belgium. Tel.: +32 32653553.

E-mail address: peter.hanselaer@kahosl.be (P. Hanselaer).

Fig. 1. Equivalent circuit of an OLED.

temperature at the frontal air-substrate interface of the OLED instead of at the internal organic layer. Another (much more complicated) method to measure organic layer temperature is Raman-spectroscopy, targeting specific molecules in the organic layers [6]. An alternative and more practical approach described in this paper, called the “local luminance derived OLED temperature” (L2DoT) method, is based on modeling the effect of temperature on luminance at fixed low voltages and to derive temperature maps from luminance maps.

2. Materials and methods

2.1. Local diode characteristics versus temperature model

2.1.1. Shockley equation

For anorganic LEDs, junction temperature of the diode can be determined *in situ* through measurement of the temperature dependent electrical characteristics, without physical or even visual access to the measured LED [7]. Note that current and voltage through the junction are well defined.

An OLED can be modeled as an array of many diodes in parallel, with resistors in between, representing the fairly high series resistance of the (ITO) transparent surface conducting electrode layer, cf. Fig. 1 [8].

In what comes, large area OLEDs are assumed to be virtually subdivided into imaginary pixels (ij), representing these local diodes. For each local diode, the forward-biased voltage U versus current I behavior can again be modeled by the Shockley equation [9]:

$$I_{ij}(U_{ij}, T_{ij}) = I_{s,ij}(T_{ij}) \cdot \exp\left(\frac{eU_{ij}}{n_{ij}kT_{ij}}\right) \quad (1)$$

The index ij denotes the identification of the (imaginary) local diode (ij) and for each diode the following characteristics can be identified: I_{ij} , local forward current; $I_{s,ij}$, local saturation current; U_{ij} , local junction voltage; n_{ij} , local ideality factor; and T_{ij} , local junction temperature.

The characteristics of each local diode could be but in general do not need to be assumed identical in order to apply the method proposed in this paper. Allowing for local variations of the parameters in the Shockley equation make the model generally applicable and reflect all sources of non-uniformity of the device. The elementary charge of an electron and the Boltzmann constant are denoted as e and k respectively. The local saturation current density $I_{s,ij}(T_{ij})$ [A/m^2] can be written as:

$$I_{s,ij}(T_{ij}) = C_{s,ij} \cdot \exp\left(\frac{-E_{a,ij}}{kT_{ij}}\right) \quad (2)$$

with $E_{a,ij}$ the local activation energy and $C_{s,ij}$ a quasi-constant factor, combining different physical parameters [7]. In the literature, it has been shown that $C_{s,ij}$ is

temperature dependent but that this variation is negligible with respect to the exponential dependency occurring in Eq. (2) [11]. It is known that for some types of junctions, the ideality factor n and saturation current I_s may change appreciably with temperature T [7]. For LEDs, however, these parameters have been reported to be more or less constant [7]. For OLEDs, the influence of temperature T_{ij} on ideality factor n_{ij} and saturation current $I_{s,ij}$ is not yet characterized in the literature. Therefore, measurements are presented in Section 3.1.

To apply the anorganic LED approach to determine the junction temperature, but now on large area OLED devices, the local current and voltage of each diode (and all other variables in the Eqs. (1) and (2)) need to be known or measured. In this way, the junction temperature could be derived at any location, and thus a full map of the temperature distribution of all imaginary diodes could be established.

However, although the overall driving current I_{ext} and voltage U_{ext} of an OLED can be easily measured, the local current through and the voltage over each of these (imaginary) local diodes are not, due to the unknown voltage drop over the local (cumulative) series resistance. Direct measurement of these local individual parameters is hard, if not impossible, in normal operating conditions. Thus, a new approach suited for OLED junction temperature measurements is needed.

2.1.2. Local voltage

Under normal operating conditions at driving currents, the voltage U_{ij} over each local junction (ij) will differ from the externally applied voltage U_{ext} , due to the voltage drop over the series resistance. In order to avoid this voltage drops and self-heating, the applied voltage should be selected within the exponential region of the current–voltage characteristic, cf. Fig. 2, thus where the local diode behavior is described by Shockley in Eq. (1). Under this condition, the (cumulative) voltage drops due to sheet resistance are negligible in comparison with the voltage drop over the junction. Consequently, each local junction voltage U_{ij} can be replaced by the same overall value, namely the externally applied (low) voltage U_{ext} :

$$\forall i, j \in IN_0 : U_{ij} = U_{ext} \quad (3)$$

when Eq. (1) is valid. Furthermore, the local currents will be then low enough to neglect the OLED self-heating.

Fig. 2. Macroscopic U – I curve of the OLED at five ambient temperatures measured in the oven.

2.1.3. Current versus luminance model

The local luminance from a pixel, L_{ij} , is expected to be linearly related to the local current through the pixel, I_{ij} , at least at moderate currents ($<100 \mu\text{A}$) [7,10,14]:

$$L_{ij} = \eta_{ij} I_{ij} \quad (4)$$

with η_{ij} the local conversion efficiency between current and luminance. Validation measurements will be presented for three OLEDs in Section 3.2 of the Results.

Eqs. (1), (2), and (4) can thus be combined into:

$$\begin{aligned} L_{ij}(U_{ij}, T_{ij}) &= \eta_{ij} \cdot C_{s,ij} \cdot \exp\left(\frac{eU_{ij}}{n_{ij}kT_{ij}} - \frac{E_{a,ij}}{kT_{ij}}\right) \\ &= \eta_{ij} \cdot C_{s,ij} \cdot \exp\left(\frac{1}{kT_{ij}} \left(\frac{eU_{ij}}{n_{ij}} - E_{a,ij}\right)\right) \end{aligned} \quad (5)$$

From this general formula in Eq. (5), it can be seen that the local luminance L_{ij} is explicitly dependent on the (reciprocal) local junction temperature T_{ij} , indicating that local luminance can be used as an indicator for local junction temperature. The implicit dependence of junction temperature on all other variables in Eq. (5) may, however, hamper the use of luminance as an indicator for the junction temperature. Therefore, experimental evidence will be given that the impact of the combined effect of the variables η_{ij} , $C_{s,ij}$, n_{ij} and $E_{a,ij}$ in Eq. (5) is negligible within the temperature interval $[24\text{--}60^\circ\text{C}]$. Under the condition of a fixed low external voltage U_{ext} , a simplified relationship between local luminance L_{ij} and local temperature T_{ij} emerges:

$$L_{ij}(U_{ext}, T_{ij}) = A_{ij} \cdot \exp\left(\frac{B_{ij}}{T_{ij}}\right) \quad (6)$$

with A_{ij} and B_{ij} constants with respect to junction temperature T_{ij} and given by:

$$A_{ij} = \eta_{ij} \cdot C_{ij} \quad (7a)$$

$$B_{ij} = \frac{eU_{ext}}{kn_{ij}} - \frac{E_{a,ij}}{k} \quad (7b)$$

In order to determine A_{ij} and B_{ij} , a calibration procedure will be required, cf. Section 3.2. With the knowledge of A_{ij} and B_{ij} , the local junction temperature T_{ij} can straightforwardly be calculated from the local luminance L_{ij} by Eq. (6).

2.2. Experimental setup

The OLED test sample (PR5102–24 Philips, Aachen, Germany) was a top-emitting OLED for lighting, with dimensions 4 by 4 cm. A transparent and conductive indium tin oxide (ITO) layer at the front is connected to the anode in a U-shape. The continuous ITO layer thus functions as an extension of the anode. The entire backside of the OLED is connected to the cathode via an opaque aluminum sheet.

L2DoT requires a calibration process. First, the U – I characteristics of the overall driving voltage and current at room temperature needs to be measured, using a Keithley 2400 Sourcemeter, to determine the appropriate external voltage U_{ext} .

Next, the OLED was placed in a thermal oven (Heraeus RVT360) capable of maintaining fixed ambient tempera-

tures in its cavity and mounted vertically with its both sides free to air using minimal contact at the electrodes in order to minimize influence of mounting on thermal behavior. The insertion transmission losses caused by the local transparency of the glass window of the oven are determined in advance by measuring the functioning OLED (when in thermal equilibrium) with and without glass window, and ranged from 84 to 87%. All luminance measurements performed on the OLED inside the oven cavity through this window are compensated for these local losses, ensuring the correspondence of the calibration data with future luminance recordings outside of the oven.

Luminance maps $L_{k,ij}$ of the OLED surface were measured at right angle through the glass window of the oven with a luminance camera (Eldim MuraTest 2211) at several ambient temperatures T_k (from room temperature to 60°). Each settled thermal equilibrium was maintained for at least 15 min, determined with a thermistor probe (Pt100 probe connected to Keithley 2510TEC), prior to the recording of a luminance map (960x1044 pixels). The light output of the OLEDs needs to be sufficiently high to ensure a reliable/reproducible luminance measurement (above camera noise level). At the same time, significant voltage drops over the series resistance need to be avoided. Thus, driven at such a predetermined fixed external voltage U_{ext} , the OLED (junction) will not heat up, and the local junction temperature $T_{k,ij}$ will stay at its ambient temperature T_k . When these conditions can be fulfilled, the constants A_{ij} and B_{ij} can be determined from the luminance maps $L_{k,ij}$ using Eq. (6) for future use.

Hence, using the now fully known Eq. (6), T_{ij} can now be determined from any luminance map L_{ij} obtained at the same overall low driving voltage U_{ext} , with the same camera used for calibration under similar experimental circumstances.

All measurements are performed in a dark room.

3. Results

3.1. U – I characteristic

In Fig. 2, the external driving voltage and current characteristics of the OLED for five different ambient temperatures (ranging from 24 till 60°C) are presented. This I – U characteristic remains constant with time below 0.5 mA. The exponential region predicted by Eq. (1) (yet applied on the external overall OLED current and voltage) is clearly noticeable. At low voltages, below 4.5 V, leakage currents dominate the U – I curve, causing the curve to deviate from the theoretical Shockley model [7]. At higher voltages, above 5.7 V, the voltage drop caused by the contact resistance of the ITO layer becomes prominent, again causing the curve to deviate from the model. However, in between 4.5 and 5.7 V an exponential relationship is found, governed by the Shockley derived Eq. (1) (normalized RMSE = 1.7%). No indication of voltage dependency in the resistance of the ITO layer was found, but ambient temperature does have an influence on this resistance.

In what follows, the same (low) external driving voltage $U_{ext} = 5.4 \text{ V}$ is always used to perform luminance measurements, as it is clearly below 5.7 V in the exponential region

and delivers a high-enough luminance above camera noise level. While driving the OLED at 5.4 V, no self-heating could be measured using a PT100 probe connected to a Keithley 2510 TEC SourceMeter. Furthermore, the I - U characteristic remained constant with time when driven at 5.4 V. In case of (self-)heating this curve would definitely move.

3.2. Calibration

In Fig. 3, L_{ij} versus $\frac{1}{T_k}$ is shown for four random chosen pixels (ij) on the OLED at k up to 5 ambient temperatures controlled by the oven, when driven at 5.4 V. Luminances L_{ij} were stable up to 0.1% over 20 min at a fixed temperature. The linear relationship observed in these graphs (normalized RMSE = 3.1%) is the explicit evidence of Eq. (6). From this relationship, the local coefficients A_{ij} and B_{ij} , cf. Eqs. (6) and (7), can now be determined for each pixel (ij) individually.

Fig. 3 exhibits an almost identical slope B_{ij} for all four diode locations ($B_{ij} = -6920 \pm 82$).

The Y-intercept A_{ij} varies slightly per pixel ($A_{ij} = 21.4 \pm 0.25$), justifying a local luminance L_{ij} model per individual pixel (ij) given by Eq. (6). This variation can be attributed to parameters $C_{s,ij}$ and η_{ij} , cf. Eq. (7a), which appears more variable with the location (ij) on the OLED.

3.3. Luminance versus current

To validate Eq. (4), the luminance L_{ij} of one particular local diode/pixel (ij) has been measured at OLED driving

Fig. 3. Calibration relationship between $L_{k,ij}$ versus $\frac{1}{T_k}$ for four virtual local diodes (shown in different colors) on the OLED surface when driven at 5.4 V and temperature controlled in the oven.

Fig. 4. Luminance L_{ij} versus (low) driving currents I_{ext} for the OLED under study at room temperature.

currents I_{ext} between 50 and 500 μ A at room temperature, cf. Fig. 4. The local conversion efficiency η_{ij} , cf. Eq. (4), is found to be fairly constant per OLED (normalized RMSE = 0.19%); local luminance L_{ij} is linearly related to driving current I_{ext} . The local current density I_{ij} evolves proportionally with the overall external OLED current I_{ext} . Thus, local luminance L_{ij} is clearly linearly proportional to local current density I_{ij} (below 0.5 mA at least).

3.4. Validation L2DoT versus IRT

In order to validate the L2DoT method, IRT was used. The OLED under test has again been mounted vertically in the oven and was driven at a nominal current of 165 mA. Mean luminance was approximately 3000 cd/m^2 after correction of the glass window insertion loss.

After stabilization – 15 min of stable ambient temperature, measured with the thermistor probe – the nominal driving current was briefly (for the duration of the 200 ms exposure time) switched to the low driving voltage 5.4 V and a luminance map was measured with our L2DoT method, avoiding significant temperature changes before measurement completion. The temperature change during 200 ms was measured to be only 0.03 °C. From the calibration data (through A_{ij} and B_{ij}) and the calibrated Eq. (6), the local junction temperatures T_{ij} can now be calculated.

Although IRT targets the glass substrate instead of the organic layers, this method measures the OLED in the same conditions, requiring a 1 s recording time, but with the glass window of the oven briefly opened for direct access.

A temperature map obtained from the L2DoT method was position aligned with an image made with the IRT device (Infrared Solution IR SnapShot). The alignment of two squares is an easy task though requires rotation, scaling and interpolation to make a perfect match. The columns in the middle of both images were compared and plotted in Fig. 5. Both results agree within the accuracy of the thermographic camera (3 °C).

3.5. OLED junction temperature evolution

The developed L2DoT method can now be applied to study the OLED junction temperature behavior during self-heating in vertical position.

Fig. 5. Identical vertical cross-section of OLED temperature maps, both luminance-based and IRT-based.

The OLED is driven at nominal current 165 mA (approximately 7.2 V) and reaches a stable luminance (and thus temperature) distribution after 480 s (8 min). At specific moments in time, cf. Fig. 6, a luminance map is recorded while briefly enforcing a voltage $U_{ext} = 5.4$ V, followed by running the OLED again at full nominal current, thus allowing it to continue self-heating towards a steady state. These luminance maps (briefly taken at 5.4 V while operating the OLED nominally at about 7.2 V) are used to derive temperature maps from.

Fig. 7 shows luminance maps taken at nominal current 165 mA (~ 7.2 V). They cannot be used for L2DoT temperature map determination (as there is no easy relationship between luminance and temperature at this variable voltage). Although the OLED initially has a homogeneous (room) temperature, cf. first subimage of Fig. 7, the luminance distribution is non-uniform from the start: The luminance pattern appears to be hollow/concave when switched on. This is due to the cumulative series resistance of the ITO electrode layer. After 480 s, the luminance pattern has gradually evolved to a stable convex shape: highest luminance in the central region of the OLED, cf. last subimage of Fig. 7. Now junction temperature of the OLED dominates the luminance distribution over the effect of series resistance. Due to heat dissipation with the surrounding glass substrate, a higher temperature will build up in the OLED center. When driven at a constant 165 mA current, this in turn causes the current density to redistribute itself towards a higher value in the OLED center; hence, a higher luminance there as well (cf. Section 3.3).

Fig. 8 shows the OLED junction temperature results after applying the L2DoT model on the measured luminance maps from Fig. 6. Note the asymmetric shape towards the top of the vertically mounted OLED, most likely caused by convection. Fig. 9 shows one vertical column of the temperature distribution derived from recorded luminance maps at different times.

4. Discussion

A method called “local luminance derived OLED temperature” (L2DoT) is proposed in which the junction temperature of an OLED can be derived from a luminance recording at a specific driving voltage. This approach is an optical extension of the electrical characterization

method on LEDs [7]. In the LED case, the diode is driven at a fixed current thus keeping the luminance constant, whilst the voltage behaves temperature dependent. In the OLED case, the overall voltage is maintained at a fixed (and low) value, while the current (and thus luminance) varies with temperature. In Fig. 4, it is shown that a linear relationship exists between current and luminance for the tested OLED, with a normalized RMS error of 0.19%, which can be regarded as sufficient confirmation of the assumption stated by Eq. (4). Further proof can be found in solar cells, where – the other way around – the generated current is linear with light intensity (and thus luminance) [11].

In Fig. 3, a linear relationship $L_{k,ij}$ versus $\frac{1}{T_{ij}}$ described by Eq. (6) is found with a normalized RMSE of 3%, confirming that the influence of implicit temperature dependencies of η_{ij} , $C_{s,ij}$, n_{ij} and $E_{a,ij}$ in Eq. (5) is negligible in the range [24–60 °C]. Thus, Eq. (6) is validated and the L2DoT method can be used to quantify the direct relation between the luminance of an OLED at a certain location and its corresponding local junction temperature.

The L2DoT method not only allows to measure the full-field junction temperature at any given moment in time of an operational OLED, but furthermore allows to dynamically study its self-heating, cf. Figs. 7–9.

It takes about the same time (8 min) for the OLED to reach its steady temperature, cf. Figs. 6–9. As the exposure time needed for a luminance map recording (at 5.4 V) is only 200 ms, the influence of interrupting the nominal driving current and self-heating (or the switched-off cooling down process) for this brief time is neglectable.

The correspondence between the measured temperature from L2DoT and IRT in Fig. 5, demonstrates the validity of our method within the measured temperature range [24–60 °C]. Although IR-thermography will target the interface of air with the glass substrate layer instead of the organic layers, the expected temperature differences will be small because the front glass layer of the OLED is very thin. Thermal calculations and simulations have shown that only a small temperature drop (of a few Kelvin) is expected in typical OLED devices for lighting [12,13]. The reason for the slightly higher temperature values for our luminance-based L2DoT method compared to the IRT method, cf. Fig. 5, could be explained by the fact that L2DoT measures at the source of self-heating – the organic layer – while IRT at the glass substrate where heat is dissipated to air.

Advantages of L2DoT are its low cost and its low demands on the experimental setup, instrumentation and data processing. Exploiting the exponential relation between luminance and reciprocal junction temperature, only luminance (and thus a camera) is needed to calculate the corresponding temperature. Furthermore, the camera used for luminance recording even does not need to be an expensive dedicated luminance camera with a specific spectral response, as long as it has a linear response.

Any optical losses in between the OLED sample and the camera are automatically remedied when the same losses were present in the calibration procedure. In this way, a practical experimental setup becomes available to observe

Fig. 6. Luminance maps (460×460 pixels) recorded at given times by briefly enforcing a low measurement voltage 5.4 V, while the vertically mounted OLED is nominally driven at a current of 165 mA (~ 7.2 V).

Fig. 7. Luminance maps (460×460 pixels) recorded at given times (without switching to a low measurement voltage 5.4 V), while the OLED is gradually heating up at a nominal driving current of 165 mA (~ 7.2 V).

Fig. 8. L2DoT temperature maps (460×460 pixels) derived from the luminance maps in Fig. 7.

462 OLED Joule heating inside a luminaire at varying environ-
463 mental temperatures, after putting the luminaire in a

temperature controlled oven and obtaining the necessary
calibration values.

464
465

Fig. 9. Vertical cross sections through the center of L2DoT temperature maps in Fig. 8 at given times, while the vertically mounted OLED is driven at 165 mA towards a thermal steady state.

Note that OLED devices behind optically transparent materials, such as glass plates in a luminaire, cannot be measured by IRT. The usefulness and accuracy of IRT for determining organic layer temperatures will furthermore decrease when temperature gradients within the substrate (and substrate layer thickness itself) increase. Some experimenters have therefore covered the OLED emitting surface with black paint in order to optimize thermal radiation emissivity for precise IRT measurements but by doing so possibly influenced the thermal behavior of the OLED itself [4,5]. The same is valid for the complicated Raman-spectroscopy technique, targeting specific molecules in the organic layers [6]. The spectroscopy method is, however, far from practical and too complex and expensive to perform day-to-day measurements. The IRT, Raman and L2DoT methods, however, require the OLED to be visually exposed (which was not the case with LED method).

The parameters A_{ij} and B_{ij} in our model do not seem to vary significantly between different OLED samples of a same production batch but they do seem to change over time and with use. These latter findings are not yet confirmed and only based on a few samples. They, however, show that recalibration will be needed in case of extended operating time. But if they indeed remain constant in for instance a fresh production batch, the L2DoT method has potential to be applied directly for in-line quality control during OLED production.

5. Conclusion

A novel and straightforward approach has been developed for measuring temperature distributions in large area OLED devices based on luminance measurements, named L2DoT. This technique has been successfully validated through comparison with IR-thermography. It allows measurement of the active organic layers while ignoring the temperature of optically transparent layers in between device and detector, such as a glass OLED substrate or a glass luminaire cover, when calibrated accordingly. This ability gives the technique an advantage over IR thermography to study thermal behavior of OLEDs in situ. Additionally,

as only relative 'light' measurements are needed, the equipment requirements for applying this technique are also rather low. The technique could be useful to detect heat dissipation problems while designing OLED luminaires or for in-line detection of thermal issues in a production environment.

Acknowledgments

We thank Philips Aachen for making some OLED samples for lighting available to us.

Jan Buytaert is financially supported by the Research Foundation – Flanders. Johan Bleumers is financially supported by the Agency for Innovation by Science and Technology (Groen Licht Vlaanderen 2020 project). We also thank the Hercules Foundation for their financial support (AKUL035).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.orgel.2013.07.032>.

References

- [1] J.W. Park, D.C. Shin, S.H. Park, Large-area OLED lightings and their applications, *Semicond. Sci. Technol.* 26 (2011) 034002.
- [2] K. Neyts, A. Real, M. Marescaux, S. Mladenovski, J. Beeckman, Conductor grid optimization for luminance loss reduction in organic light emitting diodes, *J. Appl. Phys.* 103 (2008) 093113.
- [3] P.A. Levermore, A.B. Dyatkin, Z. Elshenawy, H. Pang, J. Silvernail, E. Krall, R.C. Kwong, R. Ma, M.S. Weaver, J.J. Brown, X. Qi, S.R. Forrest, Phosphorescent organic light-emitting diodes for high-efficiency long-lifetime solid-state lighting, *J. Photon. Energy* 2 (2012) 021205–021201.
- [4] C. Garditz, A. Winnacker, F. Schindler, R. Paetzold, Impact of Joule heating on the brightness homogeneity of organic light emitting devices, *Appl. Phys. Lett.* 90 (2007) 103506.
- [5] L.S. Pohl, E. Kollár, A.S. Poppe, Z. Kohári, Nonlinear electro-thermal modeling and field-simulation of OLEDs for lighting applications I: Algorithmic fundamentals, *Microelectron. J.* 43 (2011) 624–632.
- [6] H. Tsuji, Y. Furukawa, Temperature measurements of a phosphorescent organic light-emitting diode by Raman spectroscopy, *Chem. Phys. Lett.* 488 (2010) 206–208.
- [7] A. Keppens, W.R. Ryckaert, G. Deconinck, P. Hanselaer, High power light-emitting diode junction temperature determination from current-voltage characteristics, *J. Appl. Phys.* 104 (2008) 093104.
- [8] J. Park, J. Lee, Y.-Y. Noh, Optical and thermal properties of large-area OLED lightings with metallic grids, *Org. Electron.* 13 (2012) 184–194.
- [9] W. Shockley, Theory of p-n junctions, *Bell Syst. Tech. J.* 29 (1949) 435–489.
- [10] K. Neyts, M. Marescaux, A.U. Nieto, A. Elschner, W. Lövenich, K. Fehse, Q. Huang, K. Walzer, K. Leo, Inhomogeneous luminance in organic light emitting diodes related to electrode resistivity, *J. Appl. Phys.* 100 (2006) 114513.
- [11] P. Hanselaer, W.H. Laflère, R.L. Van Meirhaeghe, F. Cardon, Current-voltage characteristic of Ti-pSi metal-oxide-semiconductor diodes, *J. Appl. Phys.* 56 (8) (1984) 2309–2314.
- [12] K.J. Bergemann, R. Krasny, S.R. Forrest, Thermal properties of organic light-emitting diodes, *Org. Electron.* 13 (2012) 1565–1568.
- [13] M. Slawinski, D. Bertram, M. Heuken, H. Kalisch, A. Vescan, Electrothermal characterization of large-area organic light-emitting diodes employing finite-element simulation, *Org. Electron.* 12 (2011) 1399–1405.
- [14] J. Jacobs, D. Hente, E. Waffenschmidt, Drivers for OLEDs, 42nd IAS annual meeting conference record, *IEEE IAS 2007* (2007) 1147–1152.