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Passive cooling of large-area organic light-emitting diodes

Philipp Schwamb [a,*], Thilo C.G. Reusch [a], Christoph J. Brabec [b,c]

[a] OSRAM Opto Semiconductors GmbH, Leibnizstrasse 4, 93055 Regensburg, Germany
[b] Institute of Materials for Electronics and Energy Technology (I-MEET), Friedrich-Alexander-University of Erlangen-Nuremberg, Martenstrasse 7, 91058 Erlangen, Germany
[c] Bavarian Center of Applied Energy Research (ZAE Bayern), Am Weichselgarten 7, 91068 Erlangen, Germany

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ABSTRACT

The authors investigated passive cooling of large-area organic light-emitting diodes (OLEDs) with special focus on convective cooling. Electro-optical and thermal behaviour of large-area OLED devices are therefore modelled using finite element method (FEM) and computational fluid dynamics (CFD) simulations. Resulting temperature and luminance distributions are compared with measurement data at different driving conditions and test setups. The investigation yields that including laterally resolved convection coefficients from CFD simulations greatly improves model accuracy compared to simpler convection estimations. These findings are important for OLED and their heat spreader design especially for features like flexible, transparent, high-power and or large-area due to their specific limitations for heat spreading and or their high heat spreading requirements.

1. Introduction

OLED technology is developing quickly in terms of luminous efficacy and lifetime. OLED based handheld displays are selling millions, TVs are reported to commence mass production and OLED based lighting is in the phase of market entry. These upcoming markets of TV and lighting are likely to push device scale towards large-area products.

The scale of area was reported to influence the heat up of devices [1]. This is critical due to temperature affecting the electro-optical properties of OLEDs. Major effects of higher temperature are increased conductivity in organics (hopping transport) and lower intrinsic lifetime meaning accelerated ageing, a decrease in current efficiency and accompanied voltage rise over operation time [2,3]. The effects on conductivity may cause severe problems for example in combination with inhomogeneous heat-up and voltage gradients along electrodes with limited electrical conductivity resulting in differential ageing and inhomogeneous luminance. Especially as these issues create and or amplify each other [4].

Apart from scale high power applications like high brightness devices increase heat generation and thus the importance of thermal management.

Furthermore, flexible or transparent OLEDs are especially critical in terms of thermal design. Flexible devices are based on very thin substrates like metal or plastic foils [5,6], transparent ones are limited to transparent heat spreading rendering heat distribution and temperature levelling more challenging.

Finally OLED cooling design is limited for most applications as flatness and energy efficiency are important features. Thus 3D cooling fins and active cooling are no options. It is therefore important to understand the available passive cooling mechanisms well in order to make best use of them.

In previous studies numerical simulations have been used to model the interactions of OLED devices and passive cooling. Electro-thermal large-area OLED device modelling using reference diode or "elementary cell" data was first

* Corresponding author. Tel.: +49 151 4020 2792; fax: +49 941 850 444 5351.
E-mail address: philipp.schwamb@osram-os.com (P. Schwamb).

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reported by Garditz et al. [4]. Recently Slawinski et al. [7] presented extensive data using the same approach. While the latter achieved decent simulation to measurement agreement a rule of thumb value of 5 W/(m^2 K) common in OLED focused reports was used to model convection. Neither of the works consider effects of air flow patterns on convective cooling. This maybe inadequate as for example Cok et al. [8] found temperature gradients from device centre towards the edges suggesting it to be an effect of convection patterns. Improved convection estimations seem therefore needed. The authors therefore investigated passive cooling of large-area OLEDs by simulation and measurement highlighting the importance of advanced convection modelling. Furthermore relatively simple ways to implement the findings into state of the art electro-thermal simulation models are described.

2. Devices and measurement

OLED devices of 175 × 42.8 mm^2 with a central active area of 152.6 × 26.4 mm^2 using 0.1 mm thin stainless steel substrates are prepared for measurements. The devices are electrically connected at three terminals on both of the far sides as sketched in Fig. 1 together with the vertical architecture: the central terminal connects to the anode, the outer ones to conductor tracks flanking the active area. These conductor tracks support current spreading for the transparent cathode between them to ensure high homogeneity of current distribution. Protection from moisture is ensured by thin-film encapsulation. A high emissivity film is applied on the back, the front is covered by a light diffuser film for mechanical protection and colour mixing. The overall thickness is less than 0.3 mm.

Two test cases as sketched in Fig. 2 are employed. In the first case the devices are thermally coupled to a hotplate of set temperature using thermally conductive paste. This condition allows to render thermal distribution and dissipation processes negligible as the thick metal hot plate controls and sets uniform temperature. In the second case devices are placed horizontally floating in still air using thin ribbon wires as support. In this setup heat is dissipated by radiative and convective cooling only.

Measurements are done at steady-state conditions using a *Keithley 2400*, a *Lumicam 1300-202 Color* and a thermographic camera *VarioCAM hr 600* as current source, luminance and temperature metre respectively. The thermographic camera was also used to determine device emissivity compared to a temperature and emissivity reference and estimate the losses at the wiring by the temperature gradients observed along it. The emitted optical power over electrical input power is measured using an integrating sphere with *CAS 1400 spectrometer*. Thermal dependence of this power ratio is assumed to scale with temperature as measured 0°-luminance to electrical power ratio does. This should be applicable for our devices with a scatter film homogenising emission. Ambient temperature was tracked for the second test of a floating device. Contact $R_{S,co}$ = 0.06 Ω/□, anode $R_{S,a}$ = 0.16 Ω/□ and cathode $R_{S,c}$ = 5 Ω/□ sheet resistances are measured using four-point-probing. The steel substrate's thermal conductivity is provided from the substrate supplier. Thus all input parameters required for our thermo-electro-optical model except convective heat dissipation are determined. Estimating the latter is discussed in the next section.

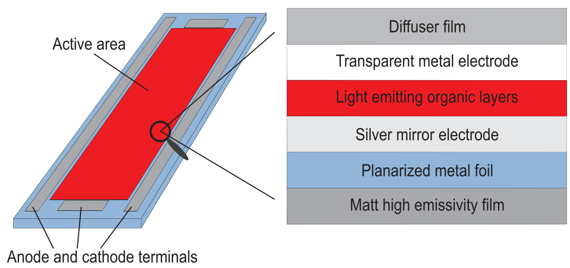

Fig. 1. Schematic showing the lateral structure (left) and the vertical architecture (right) of measured OLED devices.

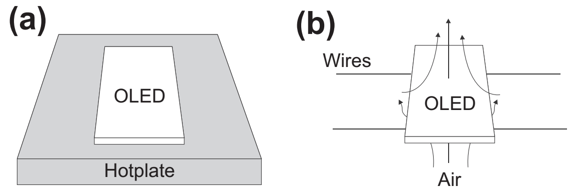

Fig. 2. Sketches of the two test setups: OLED thermally coupled to a hotplate (a) and OLED horizontally floating in air (b).

3. Simulations

Coupled thermo-electro-optical and computational fluid dynamics simulations are run using *COMSOL* [9] and *SolidWorks Flow Simulation* [10] respectively. Their models are described in this section.

3.1. Coupled thermo-electro-optical simulation

For coupled thermo-electro-optical modelling the finite elements approach pioneered by Garditz et al. [4] and extensively described by Slawinski et al. [7] is used. Accordingly the OLED is modelled by two 2D-sheets representing anode and cathode electrically connected by organics inbetween. The organics connecting the sheets are represented by measured reference diode's characteristics giving heat, current and light generation based on temperature and voltage input. This input voltage at each point of our large scale OLED simulation is derived from calculating anode and cathode potentials based on their respective sheet resistances. Using an analogous routine temperature distribution is calculated based on device's thermal conductivity simplified by 2D representation like the electrical part. The latter is reasonable due to the extreme scale of lateral (cm) to vertical dimensions (nm) and vertical thermal resistances being extremely small compared to the resistance at device-air interfaces [1]. The OLED's characteristics measured using small reference OLEDs of 8.6 × 8.6 mm^2 active area are presented in Fig. 3. Such small OLEDs are chosen for reference measurements due to their small size result-