Modeling and Simulation of Electrothermal Feedback in Large-area Organic LEDs

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***Abstract*—We present an empirical PDE model for the description of the interplay between total current and heat flow in large-area organic LEDs, which can lead to unwanted spatial brightness inhomogeneities. The model resolves the different layers in the OLED stack by taking their individual IV characteristics into account. In particular, the electrical conductivity features a field dependence to incorporate the non-Ohmic behavior of the organic materials and a temperature dependence via an Arrhenius law. We discuss the numerical scheme and present simulation results that confirm the experimentally observed S-shaped IV characteristics with regions of negative differential resistance, which cause the inhomogeneities.**

I. Introduction

Organic, i.e. carbon-based, semiconductor materials are nowadays common in smartphone displays and increasingly also in TV screens. Also lighting applications are of great interest due to the distinct properties of organic light-emitting diodes (OLEDs), e.g. large-area surface emission, semi-transparency, flexibility. However, in lighting panels much higher brightness is required than in displays and hence higher currents are necessary. These cause substantial Joule self-heating accompanied by unpleasant brightness inhomogeneities of the panels [1].

Applying a voltage to an organic semiconductor device induces a current flow, that leads to a power dissipation by Joule heating and hence also a temperature rise. Due to the temperature activated hopping transport of the charge carriers, higher temperatures improve the electrical conductivity in organic materials, such that even higher currents occur. Thus, a positive feedback loop develops, that either leads to the destruction of the device by thermal runaway if the generated heat cannot be dispersed into the environment or results in S-shaped IV characteristics. In particular, in the latter case regions of negative differential resistance (S-NDR) appear, where currents increase despite of decreasing voltages, see Fig. 1. Devices that show such an electrothermal interplay are called thermistors. In [3] S-NDR has been verified for C_{60} nin-structures and in [2] for organic materials used in OLEDs.

Due to the huge aspect ratios of OLED panels, such devices cannot be regarded as a single spatially homogeneous thermistor, but rather as an array of thermally and electrically coupled thermistor devices. The self-heating, and hence also the local differential resistance, is now a collective property of neighboring thermistors. In particular, in contrast to a spatially homogeneous setting, a new operation mode propagates through the device. In this “switched-back” mode local voltages *and* local currents are decreasing, which is eventually the reason for the development of inhomogeneities [2].

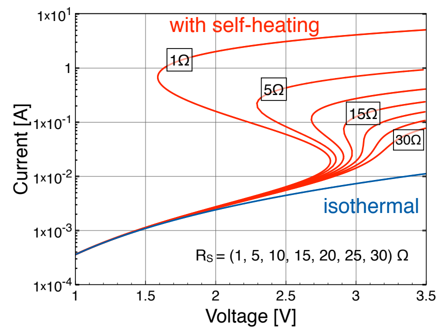

Fig. 1. Simulated S-shaped IV characteristics for a small organic nin-structure with a load resistance R_S in series (red), for $E_{\text{act}} = 8k_{\text{B}}T_a$ and different values of the load. A power law with $\alpha = 2.75$ was assumed.

An appropriate simulation tool for the electrothermal description of OLEDs can help to validate cost-efficient device concepts by accounting for nonlinear self-heating effects. In [2] the electrothermal behavior of OLEDs is simulated using SPICE and electrically and thermally coupled thermistor networks. Based on this circuit model an empirical PDE model was developed in [4] to describe the total current and heat flow in organic semiconductor devices consisting of a coupled system for the electrostatic potential and the temperature. This PDE modeling approach gives much more flexibility concerning variations in geometry and material composition than network models.

II. Thermistor Modeling

To describe the interplay of current and heat flow in OLEDs the following empirical PDE model was developed in [4]. It consists of the current flow equation for the electrostatic potential φ and the heat equation for the temperature T

$$\begin{aligned} -\nabla\cdot J(x,T,\nabla\varphi) &= 0, \\ -\nabla\cdot\big(\lambda(x)\nabla T\big) &= H(x,T,\nabla\varphi) \end{aligned} \tag{1}$$

with electrical current density J, heat conductivity λ, and Joule heat term H. The special features of the model are

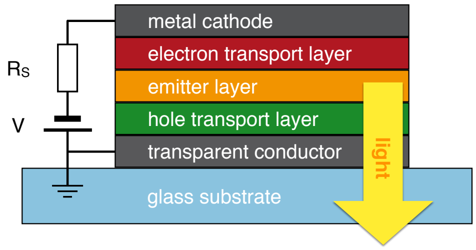

Fig. 2. Schematic OLED stack.

the Arrhenius-like temperature law as well as the non-Ohmic behavior, which is incorporated e.g. by a power law $J \sim |\nabla\varphi|^{\alpha(x)-1}\nabla\varphi$ with a material dependent exponent $\alpha(x) \geq 1$ which may jump abruptly between the different layers, see Fig. 2. However, also more general characteristics can be considered, e.g. an exponential law for the emitter layer.

The temperature dependence of the conductivity is modeled by an exponential law of Arrhenius type, which features an activation energy that is linked to the energetic disorder in the organic material

$$F(x,T) = \exp\Big[-\frac{E_{\text{act}}(x)}{k_{\text{B}}}\Big(\frac{1}{T}-\frac{1}{T_a}\Big)\Big].$$

Here, $T_a > 0$ denotes the fixed ambient temperature, and E_{act} is the material dependent activation energy, which has to be extracted from measurements.

The Joule heat term in the second equation of (1) reads

$$H(x,T,\nabla\varphi) = -\eta(x,T,\nabla\varphi)J(x,T,\nabla\varphi)\cdot\nabla\varphi,$$

where $\eta(x,T,\nabla\varphi) \in [0,1]$ represents the light-outcoupling factor, which takes into account that not all of the electric power is dissipated as heat.

III. Simulation of OLED Tabola

In Fig. 3 a horizontal cross section through the emitter layer of a large-area (7.5 cm $\times$ 15 cm) OLED panel showing the temperature distribution and the current density is given. The simulated structure is depicted in Fig. 2. Due to its low sheet resistivity, the metal cathode was replaced by Dirichlet boundary conditions. For the hole and electron transport layers a superposition of an Ohmic and non-Ohmic current law was assumed, namely

$$J(T,\nabla\varphi) = \Big(\sigma_0 F_0(T) + \sigma_1 F_1(T)\Big[\frac{|\nabla\varphi|}{E_{\text{ref}}}\Big]^{\alpha-1}\Big)\nabla\varphi.$$

The base conductivities σ_0, σ_1, the activation energies $E_{\text{act},0}$, $E_{\text{act},1}$, as well as the power law exponent $\alpha \geq 1$ are fitted to measurements of smaller samples of the respective layer. For the emitter layer, J is chosen such that the resulting characteristics correspond to Shockley's diode equation.

The pictures in Fig. 3 correspond to a stage of substantial self-heating with a significant inhomogeneity of the current density. In fact, large parts of the center of the tabola are in the switched-back mode, where the local currents through the stack are in fact decreasing.

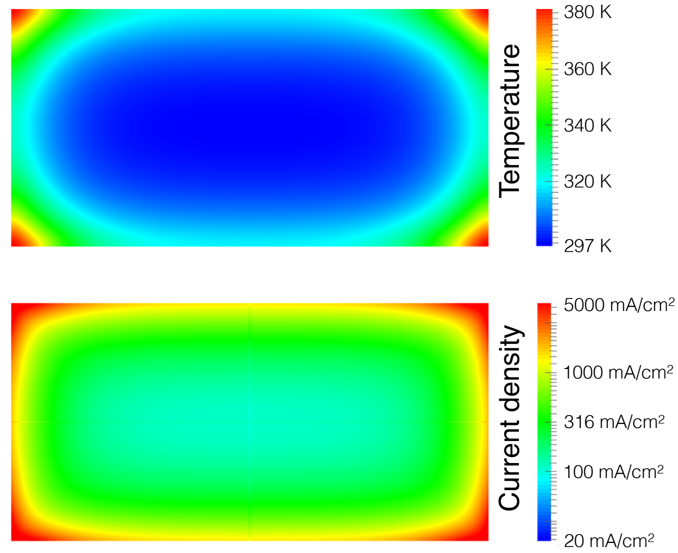

Fig. 3. Current and heat flow simulation of large-area OLED tabola.

IV. Conclusion

In all organic devices with sufficiently large activation energies, the interplay between self-heating and temperature activated hopping transport can lead to S-shaped IV characteristics with NDR regions. In large-area OLEDs this effect can promote spatial inhomogeneities of the brightness.

We presented an empirical model that is capable of describing the appearance of spatially local NDR regions in large-area OLEDs. The spatially resolved model includes the positive feedback between temperature and conductivity. The numerical solution of the PDE system is based on finite-volume methods and uses numerical path-following to trace the S-shaped IV curves. It offers greater flexibility with respect to geometry and material variations than network models. In particular, the simulation of curved OLEDs can be realized.

Acknowledgement

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