Degradation of the luminance and impedance evolution analysis of an OLED under thermal and electrical stress

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***Abstract*—Organic light emitting diodes are one of the most innovative light sources. They do not require semiconductor fabrication techniques like the LED family, they are simple to construct and are used in many original applications. The inconvenient of this product is that it does not have a long lasting useful life with more then 10000 hours. Therefore, this paper will present a parametric method to design an aging model of the OLED based on luminance decay and electrical impedance evolution. Accelerated tests using thermal factor and current density will be applied to large warm white OLED panels. A log-normal model for the luminance decay will be merged with design of experiments method to include the stress factors as well as impedance characteristics resulting in an effective degradation model that can estimate the lifetime of the OLED.**

***Index Terms*—Characterization, Degradation, Estimation, Impedance, Luminance decay, Organic Light Emitting Diodes, Parameters.**

I. Introduction

Since the invention of electricity and lighting, the number of light products has been expanding exponentially. Traditionally, incandescent light bulbs were used, where manufacturers mainly focused on the price factor in the production. Later, other technologies like fluorescent lighting provided more energy efficient systems and high-intensity discharge lamps provided higher levels of lighting over large areas. Afterwards, light emitting diodes LED, a significant energy efficient products were introduced. The LED technology has developed to be the most practical and economical lighting used in a variety of applications. From the LED family, the organic LED made its way in the semiconductor world thanks to the many benefits it gives.

As their name indicates, OLEDs are basically made of one or many layers of organic materials between a sheet of cathode and anode on a transparent substrate [1]. The major advantage of organic materials is that they can be deposited by evaporation and spin coating leading to an easier and cheaper production [2]. Several promising OLED technologies can be cited to make either displays or panels. Konica Minolta, a Japanese company manufacturing business and industrial imaging products, developed ultra thin flexible OLED panels [3]. Kunić et al. presented various OLED technologies used as displays, and compared it to other TV display technologies as Plasma and LCDs [1]. From this paper, one promising technology other than the flexible OLED is the transparent OLED that can be used in tables or heads-up displays as it emits light in both directions.

However, the organic materials of the OLED have a major drawback. They are extremely sensitive to several factors such as moisture, oxygen, dust, temperature, and current density due to charge/carrier balance and so on [4]... Some extrinsic factors such as humidity, dust or oxygen can be alleviated using proper encapsulation. An adhesive matrix with moisture and oxygen absorbent fillers was used to encapsulate an OLED display without affecting its characteristics in [5] for example. Yet, the organic materials can not be directly protected against temperature and current density, which remains a huge inconvenient leading to luminance and impedance degradation of the OLED. Most OLEDs nowadays do not have lifetimes longer than 10000 hours.

The luminance degradation and the voltage rise were studied under several current density levels, results [6] indicated a significant increase of the formers under the effects of the latter. Likewise, the influence of temperature on degradation mechanisms of the OLED was studied.Ishii et al. proved that at a fixed current density, the higher the temperature, the faster the luminance decay [7].

This decay can be used as an aging indicator, as reported in the papers mentioned previously. However, the equivalent electrical circuit of the OLED can be used as well. Buso et al. [8] worked on a equivalent model for large signal LEDs comprising a series resistance, associated with a capacitor in parallel with another resistance. For example, in [9], the impedance of the OLED was measured during the aging under

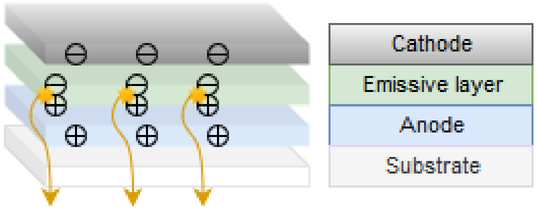

Fig. 1. 2D section diagram of a single layer OLED

thermal and electrical stress. As a result, the series resistance of the device had the most significant increase with aging.

Our paper objectives are to link the luminance decay of an OLED with its electrical characteristics, making a very descriptive, yet easy model. To do so, and based on the studies previously mentioned , different current density levels will be applied to an OLED under a high temperature level in order to perform accelerated testing. Such test method is used to minimize the total measuring time. It uses stress factors higher than the norms to surge the fatigue, thus increasing the degradation process [10]. Luminance measurement and impedance characterisation of the OLED before and during the aging process will be done.

The remaining of this paper is organised as follows: section II describes the OLED technology, its physical specifications and its aging modelisation. Section III describes the study and the design of experiments to be conducted. Section IV describes the experimental test bench, and the results, plus the models found. Section IV at the end, a conclusion on the methods and models found is made clear.

II. OLED TECHNOLOGY

The OLED consists of a transparent substrate layer (glass or plastic), a transparent anode (usually made of an indium-tin-oxide ITO), one or many emissive layer made of organic molecules (polymer) and a metallic cathode (aluminium, calcium, magnesium). The anode and cathode are respectively holes and electron transport. The recombination of the two entities occurs in the emissive layer, and a photon is produced (Fig.1).

A. OLED's equivalent electrical model

The structure of the OLED, can be represented by an equivalent electrical circuit. Bender et al. modeled an equivalent circuit with and without leakage resistance for a small signal and a large signal OLED [11]. Basically, an OLED has a series resistance representing the ohmic losses, a capacitor representing the off state of the diode in parallel with an ideal diode and eventually leakage resistance. When an OLED has multiple emissive layers, the equivalent circuit will include more blocks of resistances-capacitors. Alchaddoud et al. worked on a multi-layer model with two resistance-capacitor blocks [12]. For the aging purpose, the diode will not be presented and multiple layer model is considered. This model is presented in Fig.2 where Rs is the series resistance, $Rp1$ and $Rp2$ are the parallel resistances and $Cp1$, $Cp2$ are the parallel capacitance.

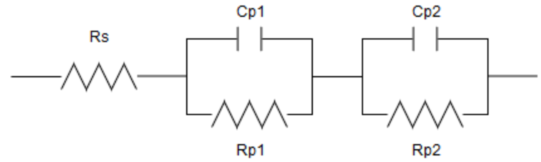

Fig. 2. Equivalent electrical circuit of a multiple layer OLED

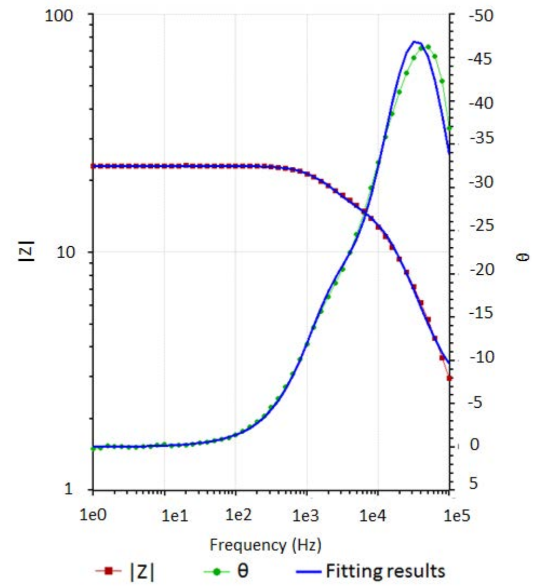

Fig. 3. Bode diagram of the studied OLED panel and the fitting result of its equivalent circuit

The impedance of the equivalent circuit will be (based on [12]):

$$Z = Rs + \frac{Rp1}{1 + (\omega \cdot Rp1 \cdot Cp1)^2} + \frac{Rp2}{1 + (\omega \cdot Rp2 \cdot Cp2)^2} \quad (1)$$

Although the impedance of the equivalent circuit can not be directly measured, it is related to the frequency applied to the circuit. Therefore, a bode diagram could solve the equation by a fitting method. Figure 3 represents a bode diagram of a tested OLED from Oledworks Brite 1 FL300 warm white type and the fitting result based on the circuit of figure 2. The two capacitor-resistance blocks proved to have the best fitting results. Thus the circuit of figure 2 will be adopted in the following. This method is adopted in [12]. Other papers like [11] did a typical method by plotting an *I-V* curve and a voltage-time plot to identify the parameters of the OLED, but the model adopted in this paper is more complicated than the model adopted in this paper thus a bode diagram is sufficient.

B. Degradation model of the OLED

The degradation model of an OLED is needed in order to estimate the useful life of the device, as well as designing a convenient corresponding driver. Ossila, a company that develops organic LEDs for academic and industrial uses, published a brochure for testing not only the performance of the OLED but its lifetime [13]. The company proposed two methods for modeling the lifetime of the OLED:

- The first method is taking initial data of the luminance decay, then stretching it to fit a model (in their case, they used a stretched exponential decay (SED)).
- The second method is based on accelerated testing where the lifetime of the OLED under extreme stress levels is rapidly attained, and by an acceleration factor, one can find the lifetime under normal stress levels.

Xu et al. used the accelerated method for sealed OLED at different current density levels [6] and used the SED at different current density and temperature levels [7]. A modified SED was applied to a flexible OLED in [14] to describe all the phases of its degradation mechanism. Lognormal model can be fitted as well, to the luminance decay of the OLED. The latter model was employed to accelerated constant current stress in order to estimate the lifetime of warm white OLEDs [15].

Like the previous papers, the OLED decay in our case is surveyed by monitoring the luminance.Only extreme stress levels are applied, so the second method can not be applied. Hence the fitting method will be applied with a lognormal model. (2) represents its distribution function. μ and σ are respectively the mean and standard deviation of the normal distribution and t is the time.

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \exp^{-\frac{1}{2}(\frac{log(t)-\mu}{\sigma})^2} \tag{2}$$

III. Design of experiments

Until now, all the models proposed are time varying models that does not link the current density level nor the temperature. Here comes the turn of design of experiments (DOE). The DOE methodology was introduced by Fisher [16] that needed an optimal plan to conduct the experiments in the agriculture field. It then was developed for a lot of applications, including the aging process.

The DOE allows to obtain a parametric modeling of a response depending on several factors on the lowest experimental cost. Considering that the log-normal model chosen previously does not have any relation to the stress factors applied, the DOE is the best suited method to connect a time varying model to a factor varying one.

The factors are the different stress applied to the device and the interaction between these stresses. The DOE treats only the critical points of each factor sot that every experiment involves all the factors. Thus, the number of experiments to be conducted are related to the number of factors and the number of levels for each factor like the equation 3, where N is for the number of experiments to conduct, k is for the number of levels for each factor and n is the number of levels sharing the same number of factors. A linear model needs two levels. Factorial planes have more than two levels, but the most used are the two level planes since they require a minimum number of experiments while guaranteeing a good quality of the model.

Fig. 4. rectangular Brite 1 FL300L ww OLED from oledworks

$$N = k_1^{n_1} \times k_2^{n_2} \times ... \tag{3}$$

Each experiment is linked to a state where each factor has a position that is ascending respectively with its level. The mathematical relation given in equation 4 provides the effect of the factors

- M as the mean of the results
- E_1 till E_N as the different factors and the interaction between each factor.

Y_1 till Y_N are the results taken for the learning of the factors. Salameh et al. [17] considered Y as the time when the luminance of the OLED decays in 30 %. p_{1_N} ... are the position assigned to the factor ate each experiment. For example, if a factor has 2 levels, the positions will be $p_{11} = -1$ and $p_{21} = +1$, and so on, where the column index refers to the factor number and the line index refers to the experiment number.

$$\begin{bmatrix} 1 & p_{11} & \cdots & p_{1N} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & p_{N1} & \cdots & p_{NN} \end{bmatrix} \times \begin{bmatrix} M \\ E_1 \\ \vdots \\ E_N \end{bmatrix} = \begin{bmatrix} Y_1 \\ \vdots \\ Y_N \end{bmatrix} \tag{4}$$
$$\begin{bmatrix} P \end{bmatrix} \times \begin{bmatrix} E \end{bmatrix} = \begin{bmatrix} Y \end{bmatrix}$$
$$\begin{bmatrix} P^{-1} \end{bmatrix} \times \begin{bmatrix} Y \end{bmatrix} = \begin{bmatrix} E \end{bmatrix}$$

After finding the effect of each factor, the result wanted to be predicted can be found by the equation 4.

The results needed in our case are the parameters of the log-normal equation, hence the $[Y]$ will be a matrix of two columns and N lines. the first column will refer to the μ and the other will be σ.

IV. Motivating example

A. Experimental data

The OLEDs tested for the purpose are Brite 1 FL300L warm white OLED panels from Oledworks (figure 4). The specifications are presented in table I.

B. Pre-study on the design of experiments

As it was mentioned in [18], a DOE should plan the whole experiment. The stress levels to use, the proportion of devices at each stress level, the time of measurements while aging and the total number of devices to be tested need to be determined *a priori* before starting the tests.

TABLE I
SPECIFICATIONS OF BRITE 1 FL300L WW OLED PANEL FROM OLEDWORKS

Name	OLEDWorks Brite 1 FL300L ww integration level 2
Light surface area	$22.4 \times 4.6\ cm$
Colour	warm white
Colour temperature	$2900\ K$
Nominal current	$368mA$
Maximum curret	$390mA$
Voltage	$24\ V$
Luminous efficacy	$42\ lm/W$@$368\ mA$
Maximum operational temperature	$40°C$
Lifetime	$10000h$ @ $368mA$

TABLE II
THE CURRENT DENSITY AND TEMPERATURE LEVELS TO BE TESTED FOR THE DOE

Current (mA)	Current density ($mA\backslash cm^2$)	DOE level
450	4.37	-1
520	5.04	0
600	5.82	$+1$

Temperature ($°\ C$)	DOE level
40	-1
60	$+1$

The stress levels used are temperature and current density. The maximum operational temperature of the OLED is $40°C$, thus and in order to accelerate the decay process, the operational level will be $60°C$ as well as $40°C$. As for the choice of the current density levels, Salameh et al. studied lifetime DOE models using several number of levels [17]. It concluded that a 3 levels factorial plan had a better results for predicting the lifetime. Hence, Three current density levels are used for the DOE, thus $N = 3^1 * 2^1 = 6$ OLEDs are needed. For statistical uncertainties, several repetition at each stress level should be considered. But, for material reasons, only one OLED will be allocated to each stress levels. Besides the learning set, two OLEDs will be used for validating the model set, making a total of 8 OLEDs. The levels of the current density and temperature to be tested for the DOE are summed up in the table II.

As for the time of measurements a pre-study defining an *a priori* lifetime should be done. To do so, the priori lifetime will be based on the Brite 1 FL300L ww datasheet [19]. In the datasheet, there is the lifetime of the OLED operating at $135\ mA$ and $368\ mA$ at an ambient temperature. Thus, it is possible to determine the accelerated model proposed in section II-B. This model is represented in (5) where L_0 is the initial luminance at a specific current density, $LT70$ is the lifetime where the luminance reaches 70% of its initial luminance and n and C are constant related to the OLED.

$$L_0^n \times LT70 = C \tag{5}$$

In order to determine the constants of the model (5), the initial luminance is measured at $135\ mA$ and $368\ mA$ and is presented in the table III as well as the lifetime mentioned in the datasheet. By solving the equation 5 using the data from table III, the constants n and C would be:

- $n = 1.694$
- $C = 1.898 \times 10^{10}$

TABLE III
INITIAL LUMINANCE AND LIFETIME OF THE OLED AT 135 mA AND $368mA$

Current (mA)	Initial luminance (cd/m^2)	Lifetime LT70 (hrs)
135	1965	50000
368	5081	10000

TABLE IV
INITIAL LUMINANCE AND ESTIMATED LIFETIME OF THE DOE CURRENT LEVELS AT $23°C$

Current (mA)	Initial luminance ($cd\backslash m^2$)	Estimated LT70 (hrs)
450	8961	3824
520	10348	2997
600	11887	2369

After determining the constants of the accelerated model, the pre-estimated lifetime of the OLEDs at the currents defined in table II can be found by simply measuring the initial luminance at these currents. The estimated lifetime at ambient temperature of $23°C$ as well as the corresponding initial luminance for each current level is presented in table IV. Although the tests are conducted at a temperature level much higher then the ambient one, the lifetime can be still an index to determine the measurement time and frequency of the experiment. The logarithm of the smallest lifetime is considered and it is divided into 15 equal yet feasible portions.

C. Results and discussion

An experimental bench (figure 5) was developed at the LAPLACE laboratory to apply thermal and electrical stresses to the OLED simultaneously. The testbench consists of thermal chambers that are controlled by a regulator to keep the temperature at a constant value. These chambers has electrical outputs that are connected to DC current sources. The boxes are thermally isolated and painted black inside to prevent from light reflection (figure 6). Small fans are placed inside these chambers to verify the homogeneous distribution of the temperature.

Aging takes a lot of time and results are in progress. The results, the luminance decay model, the equivalent circuit variation model and the link between them will be presented in the final version of the paper.

1) Luminance decay analysis: Luminance decay analysis will be presented when full data is acquired.

2) Impedance evolution analysis: The impedance of the OLEDs are measured inside a Faraday cage to limit all noise sources, using the device Solartron analytical Modulab XM MTS (Figure 7. OLEDs used has an initial impedance presented in table V.

The impedance evolution of an OLED tested at the maximum conditions of $I = 650\ mA$ and $T = 60°C$ over

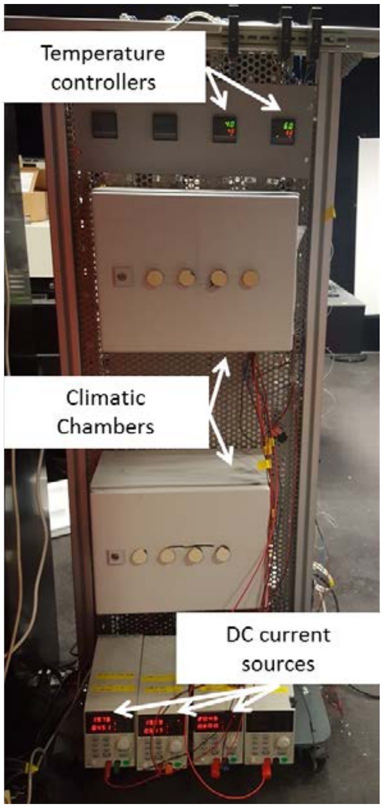

Fig. 5. Experimental bench of the OLED aging tests

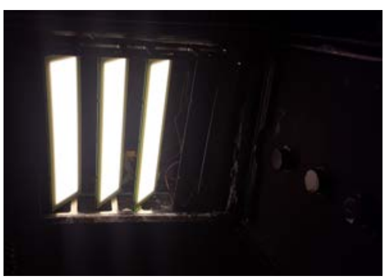

Fig. 6. Inside of a thermal chamber where 3 OLEDs are being tested

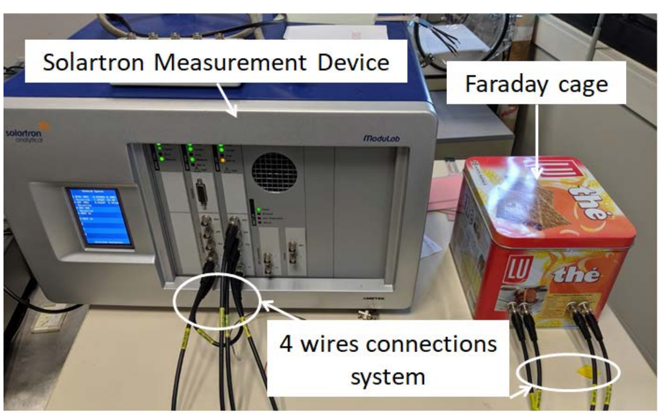

Fig. 7. Impedance measurement device with its Faraday cage

TABLE V
OLEDs INITIAL IMPEDANCE FITTING RESULTS

	Mean	Standard deviation
Rs (Ω)	2.824	0.148
Cp1 (μF)	0.8996	0.0144
Rp1 (Ω)	12.08	0.315
Cp2 (μF)	9.962	0.202
Rp2 (Ω)	9.037	0.2344

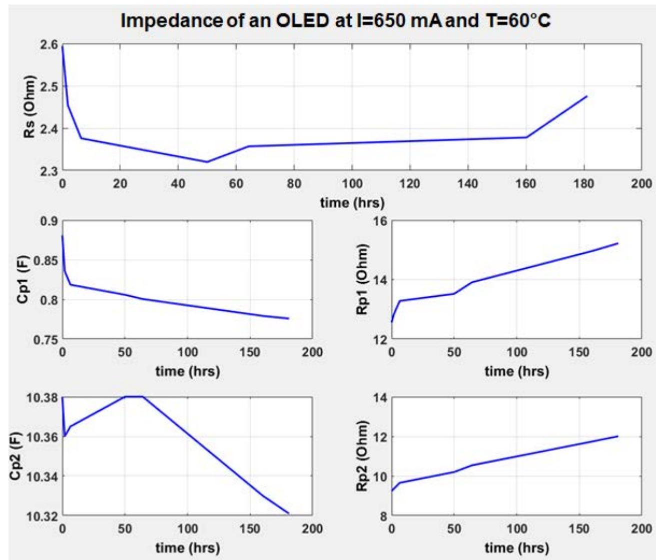

Fig. 8. Impedance evolution of a tested OLED at $I = 650\ mA$ and $T = 60°C$

180 hrs is presented in figure 8. This OLED will be used to validate the DOE model estimated later. Although the results are only a primary results from the first 180 hours, it is clear that the value of the parallel resistances is increasing linearly with time. On the other hand, the value of the parallel capacitances is slowly decreasing with time. This is a proof that leakage of charges is done through layers decreasing the capacitance. Accumulated charges through time at the emissive layer may decrease the area of recombination of electrons and holes. These accumulations can affect the resistance and the capacitance that are respectively inversely proportional and proportional to the surface. The series resistance includes several resistance, starting from the wires to the resistance added by the manufacturers respecting the standards and the equivalent series resistance of the OLED. It has a bathtub curve that is slowly increasing after 50 hours. The evolution cause of the series resistor is similar to that of the parallel resistors. The path of the impedance will be presented when full data is acquired.

3) Discussion: In this subsection, the link between luminance decay and impedance evolution is studied. Estimation of the model is presented as well.

V. Conclusions and perspectives

In this article, we proposed a method to model the aging of the organic LED based on luminance decay and impedance variation. A pre-study used an accelerating model to estimate the lifetime of the LEDs used based on the datasheet. A lognormal designed model the time varying aging process of the OLED. *'a note on how the result was linked together will be added in the final paper'*.

The advantages of our method is to first link a time varying model to a stress varying one in a simple way. It also has the advantage of predicting the impedance from just measuring the luminance and *vice versa* limiting the materials and tests to be done in the future. The paper leaves several perspectives for the future. The first perspective is to link the dimensions of the LED into the degrading model and study the influence of big surface on the aging of the LEDs and its homogeneity. Another perspective would be to test the diversity of the model using different types of OLEDs. One can also incorporate into the degradation process the colour temperature variation of the OLED which can be a very useful index for the light business.

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References

[1] S. Kunić and Z. Šego, "OLED Technology and Displays," *ELMAR, 2012 Proceedings 12-14 September*, no. September, pp. 31 – 35, 2012.

[2] B. J. Norris, "characterisation of light emitting devices," Ph.D. dissertation, Oregon State University, 1999.

[3] Hiromoto, J. Fukawa, and T. Tsujimura, "Development of flexible OLED," *Proceedings of AM-FPD 2014 - The 21st International Workshop on Active-Matrix Flatpanel Displays and Devices: TFT Technologies and FPD Materials*, pp. 21–24, 2014.

[4] S. C. Xia, R. C. Kwong, V. I. Adamovich, M. S. Weaver, and J. J. Brown, "OLED device operational lifetime: insights and challenges," 2007.

[5] Y. Zhang, M. Andreasson, H. Zhou, J. Liu, T. Andersson, and J. Y. Fan, "Encapsulation of OLED device by using anisotropic conductive adhesive," *International Symposium on High Density Packaging and Microsystem Integration 2007, HDP'07*, pp. 5–8, 2007.

[6] X. M. Xu, W. Q. Zhu, Q. Wang, Z. L. Zhang, and X. Y. Jiang, "Study on the degradation of sealed organic light-emitting diodes under constant current," *2009 International Conference on Electronic Packaging Technology and High Density Packaging, ICEPT-HDP 2009*, vol. 3, pp. 778–781, 2009.

[7] M. Ishii and Y. Taga, "Influence of temperature and drive current on degradation mechanisms in organic light-emitting diodes," *Applied Physics Letters*, vol. 80, no. 18, pp. 3430–3432, 2002.

[8] D. Buso, S. Bhosle, Y. Liu, M. Ternisien, C. Renaud, and Y. Chen, "OLED electrical equivalent device for driver topology design," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1459–1468, 2014.

[9] P. Dupuis, A. Alchaddoud, L. Canale, and G. Zissis, "OLED ageing signature characterization under combined thermal and electrical stresses," *Proceedings of the International Symposium on Electrical Insulating Materials*, pp. 311–314, 2014.

[10] G. Huairui and A. Mettas, "Improved reliability using accelerated degradation & design of experiments," *Proceedings - Annual Reliability and Maintainability Symposium, RAMS*, pp. 446–450, 2007.

[11] V. C. Bender, T. B. Marchesan, and J. M. Alonso, "Solid-State Lighting: A Concise Review of the State of the Art on LED and OLED Modeling," *IEEE Industrial Electronics Magazine*, vol. 9, no. 2, pp. 6–16, 2015.

[12] A. Alchaddoud, G. Ibrahem, L. Canale, and G. Zissis, "Impedance Spectroscopy and Evolution of the Equivalent Electrical Circuit Model for Large Area Organic Light Emitting Diodes Aged under Stress," *Proceedings - 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018*, pp. 1–4, 2018.

[13] Ossila, "OLEDs, Materials and guides to enable your research [brochure]," Ossila, Tech. Rep., 2017.

[14] H. Kim, H. Shin, J. Park, Y. Choi, and J. Park, "Statistical modeling and reliability prediction for transient luminance degradation of flexible OLEDs," *IEEE International Reliability Physics Symposium Proceedings*, vol. 2018-March, no. Eq 1, pp. 3C.71–3C.76, 2018.

[15] J. Zhang, F. Liu, Y. Liu, H. Wu, W. Wu, and A. Zhou, "A study of accelerated life test of white OLED based on maximum likelihood estimation using lognormal distribution," *IEEE Transactions on Electron Devices*, vol. 59, no. 12, pp. 3401–3404, 2012.

[16] R. Fisher, *The Design of Experiments*. Edinburgh, U.K.: Oliver and Boyd, 1935.

[17] F. Salameh, A. Picot, P. Maussion, L. Canale, G. Zissis, and M. Chabert, "Parametric lifespan models for OLEDs using Design of Experiments (DoE)," *IEEE Industry Applications Society Annual Meeting (IAS)*, pp. 1–11, 2018.

[18] M. Boulanger and L. A. Escobar, "Experimental design for a class of accelerated degradation tests," *Technometrics*, vol. 36, no. 3, pp. 260–272, 1994.

[19] *OLEDWorks LLC*, Lumiblade OLED Panel Brite FL300 ww, E353273 datasheet, 2016.