EFFECT OF DISCHARGE TIME ON THE LUMINANCE OUTPUT OF ORGANIC LIGHT EMITTING DIODE (OLED)

M.M. Azrain[1], M.R. Mansor[1], L.M. Lim[2], S. Zambri[2], B. Cosut[3] and D. Sivakumar[1]

[1]Faculty of Mechanical Engineering,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]JABIL Circuit Penang,
Bayan Lepas Industrial Park, 11900 Bayan Lepas,
Pulau Pinang Malaysia.

[3]Faculty of Science,
Gebze Technical University, Gebze,
41400 Kocaeli, Turkey.

Corresponding Author's Email: [1]azrain.mohammad@gmail.com

Article History: Received 4 September 2018; Revised 11 July 2019; Accepted 5 October 2020

ABSTRACT: Due to its thin geometry, the luminance output of an OLED can be profoundly affected by the presence of unwanted charge due to capacitance effect. Thus, the optimum discharge time is necessarily crucial to be identified, so that the occurrence of the surplus charge can be fully terminated. However, studies on the discharge time of OLED were occasionally reported, indicated that this issue remains unexplored. Therefore, the objective of this paper was to study the effect of discharge time on luminance output of OLED. In this study, the on/off cycles approach was employed by which the OLED samples were switched-on (T_{on}) and -off (T_{off}) at specific times. With constant voltage and current supply, the Ton was fixed at 1 s, whereas the T_{off} were validated at 1 s, 10 s, 20 s, 30 s and 40 s. The stability of luminance output was captured by using a chroma-meter, carried out in an in-house black-box. The optimum discharged time was found at T_{off} 40 s and the results demonstrated that the luminance output was mostly dependent on the discharge time. The attained data emphasized the significance of determining the optimum discharge time of OLED to ensure the luminance output is accurate and reliable.

KEYWORDS: *Discharge Time; Capacitance Effect; OLED; Luminance*

1.0 INTRODUCTION

Since the first invention of organic light emitting diode (OLED) by Tang and vanSlyke [1] at Eastman Kodak, this high-end technology is still undergoing rapid development and improvement [2-4]. OLEDs are hugely demanded as they can provide an energy-saving solution and forecasted to be the next-generation technology for display and lighting applications [5-7]. In addition, OLEDs only consume electrical power as low as 0.01 W during their operation cycles [8]. This situation corresponds to almost 60 and 8 times lesser than the electricity consumption of conventional incandescent lamps and the existing LEDs, respectively. On top of that, the light produced by OLEDs is diffused into a large surface, which resulted in no glare-effect and is gentle to the eyes [9-10]. Because of the energy is uniformly applied over a large area, the temperature rise during operation is relatively small. Thus, OLEDs produce an efficient heat dissipation as compared to the inorganic LEDs [11-12]. To date, OLEDs have captured a substantial interest from the worldwide lighting and display industries including Philips, Osram, GE Lighting, Panasonic, Novaled, Mitsubishi and many other companies [13-16]. Nevertheless, due to the technical complexity and design challenges for practical uses, it is not surprising that OLED applications are considerably limited. Moreover, OLEDs' lifetime and durability have always been a significant drawback towards their commercialization success. OLEDs are negatively affected by the presence of water vapor, humidity, moisture and impurities, as well as when operate continuously under high electricity [17-20].

The lifetime of an OLED is commonly conveyed and discussed with respect to the luminance degradation rate (duration of luminance to be reduced to half of its initial value). It is typically denoted as T50 (or LT50), which is concurring with the first published paper on OLED device in 1987 [1, 10]. Thus, this condition implies that the lifetime of an OLED is directly correlated with the luminance output [21-22]. In addition, one of the major factors that can significantly influence the luminance output of an OLED which is often overlooked is the discharge time of the device due to capacitance effect.

The capacitance effect is an unavoidable phenomenon by which the unwanted charge is generated and stored between two parallel conductive materials in an electronic part. Commonly, this unwanted charge is also termed as stray capacitance or parasitic capacitance [23-24]. This phenomenon is likely to occur, especially between two highly conducting cathode and anode plates due to their closed proximity to each other [25]. Principally, when the two conductors of different voltage potentials are closely placed to one another, they can be affected by each other's electrical field. Henceforth, they act like plates of a capacitor and able to store charge for a certain amount of time (acting as a temporary capacitor). Consequently, the presence of surplus charge causes the behavior of a circuit component to be deviated from its ideal roles and resulting in the change of intended output of a device [23]. Hence, a sufficient time is needed, so that the unwanted charges can be fully discharged.

In the case of OLED devices, the luminance output is intensified as the unwanted charges increase the energy within the OLEDs for not having a sufficient time to be completely discharged. Additionally, since most of the thickness of OLED layers are normally less than 500 nm [26], this inevitable phenomenon must be highly taken into consideration while conducting experiment. In this way, incorrect measurements of the luminance output can be prevented.

A few previous studies particularly on the capacitance behavior of OLED devices had been conducted. Shrotriya and Yang [27] found that the capacitance-voltage (C-V) performance of OLEDs was mostly dependent on the chosen material of the cathode plate. In this study, they utilized different types of material including calcium (Ca), aluminum (Al) and gold (Au) as the cathode plate. Two years later, Garcia-Belmonte et al. [28] also carried out a relatively similar study specifically on the effect of cathode metal on the capacitance of OLEDs at a different applied voltage. They utilized a few cathode metals such as Au, Al, silver (Ag), magnesium (Mg) and barium (Ba), which allowed them to vary the metal work function over an energy range of 2.5 eV. At low-frequency region of the capacitive response, Garcia-Belmonte and his co-researchers had discovered that the C-V curves of the OLEDs showed a dependency on the cathode work function. The crossover of the inductive readings switched from positive to the negative values.

On the other hand, Tsai et al. [29] studied the capacitance behavior of different structure of OLEDs (two- and four-layers) at a low frequency. They revealed that the OLED's capacitance became larger as the supplied voltage was higher than the built-in voltage due to diffusion capacitance. According to Tsai et al. [29], this event was caused by the super thin structure of the OLED's thickness itself. On the other hand, Bender et al. [30] had proposed a method to acquire the intrinsic capacitance based on the theoretical equivalent model. Meanwhile, Zhou et al. [31] had successfully presented the numerical analysis based on the master equation a year later.

However, it can be noted that no systematic studies are focusing on the discharge time with regards to the presence of parasitic capacitance. This indicates that the understanding on this crucial issue, specifically in the OLED field remains unexplored. Therefore, the objective of this paper is to study the effect of discharge time on the luminance output of OLED through the on/off cycles approach. The findings of this study may provide a fundamental knowledge of the capacitance effect, as well as highlights the importance of determining the optimum discharge time for accurate assessment of OLED performance.

2.0 METHODOLOGY

2.1 OLED Material

In this study, a batch of commercially available OLED panels were employed. OLED with a dimension of 53 mm × 55 mm (± 0.3 mm) was fully encapsulated with a glass encapsulation layer and produced the luminance area of about 46 mm × 46 mm. The efficacy of these OLED samples was approximately about 60 lm/W with color rendering index (CRI) of 90 Ra at correlated color temperature (CCT) of 2700 K. As claimed by the manufacturer, this OLED is able to sustain a lifetime up to 40,000 hours when operated in a room temperature of 25°C with a constant current density of 1.89 mA/cm^2.

Figure 1 shows the Focused-Ion Beam (FIB) cross-sectional view of the OLED samples through Field Emission Scanning Electron Microscopy (FESEM) analysis. As can be noticed, the OLED has a single organic layer made up of polymer-based material from poly (p-phenylene vinylene) (PPV) group with a nominal thickness of 400 nm. Meanwhile, the reflective cathode and transparent anode of this particular OLED utilizes aluminum-based (~200 nm) and metal zinc-based material (~130 nm), respectively.

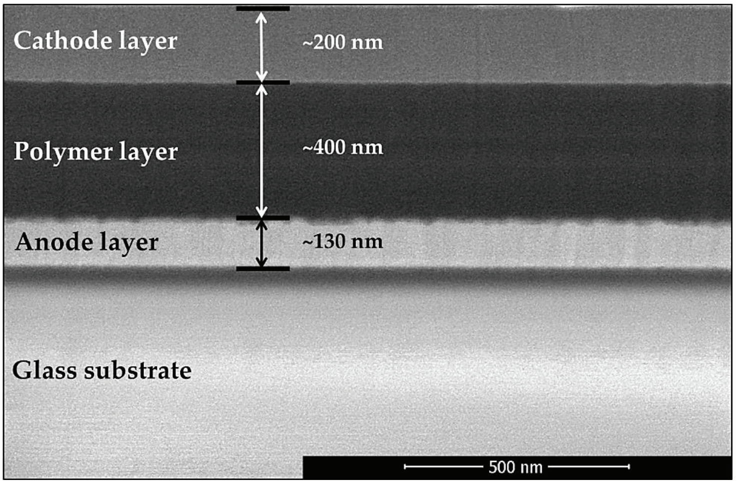

Figure 1: Configuration of the OLED sample

In a single layer of OLED structure, the polymer layer is functioned as a transport layer. When an electrical current is applied, the positively charged holes and the negatively charged electrons from the anode and cathode, respectively, are transported into the mutual organic layer. At the same time, the organic layer becomes the formation site of exciton and photon. Later, the emitted light is passed through the transparent glass substrate.

2.2 Discharge Time Test

For the discharge time test, the on/off cycles approach was employed. As mentioned earlier, the unwanted surplus energy in an electronic component requires an appropriate time to be fully discharged. Hence, through this method, the OLED panels were repeatedly switched-off at a specific time for 25 cycles. In this way, the optimum discharge time can efficiently be determined based on the behavior of the luminance outputs. Thus, the accuracy of the luminance readings in this experiment was thoroughly depending on the sensitivity of the apparatus used to capture the luminance of the OLED samples (which in this study, the chroma-meter).

As exemplified in the cyclic diagram of Figure 2, the taken time for the samples to illuminate (T_{on}) was fixed at 1 s since it only took about 1 s for these particular OLEDs to be entirely stabilized. On the other hand, several switch-off time (T_{off}) were validated specifically at 1 s, 10 s, 20 s, 30 s and 40 s. The luminance readings of the OLED samples were recorded for each cycle.

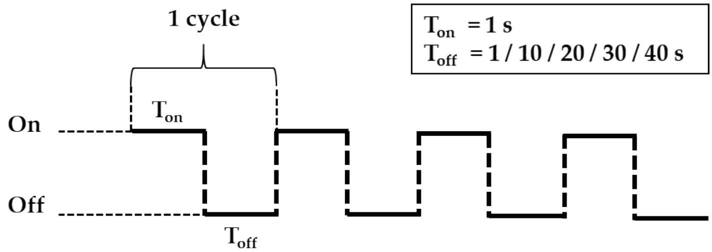

Figure 2: Cyclic diagram of the on/off cycles approach at fixed T_{on} and different T_{off}

2.3 Black-Box Apparatus Setup

Based on the standard set-up conditions of International Electrotechnical Commission – Part 6-1: Measuring methods of optical and electro-optical parameters (IEC 62341-6-1) [32], the luminance output of the OLED samples was required to be captured in a dark space. This is to ensure that there is no presence of light pollution (excessive light sources from surroundings) while conducting a particular test. Therefore, an in-house black box as shown in Figure 3 was fabricated specifically for this purpose.

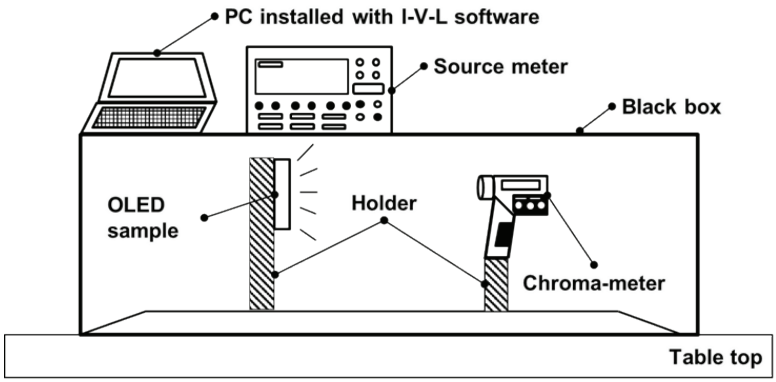

Figure 3: Schematic diagram of the in-house black-box setup

The black box apparatus was equipped with a chroma-meter (Konica CS-100A), a source meter (Keithley 2400), connectors and holders, as well as a personal computer (PC) which had been installed with an industrial-customized current-voltage-luminance (I-V-L) characterization software. All this individual electronic equipment had been properly coordinated, so that they were compatibly connected and synchronously operated. As the OLED was activated, the luminance output was automatically captured by the chroma-meter. Then, the obtained data was simultaneously recorded in the PC through the I-V-L software. As suggested by the manufacturer, the applied voltage and

current were kept constant at 8.5 V and 40 mA, respectively throughout the test (current density of 1.89 mA/cm2). All the measurements were taken at a room temperature of
25 °C, 60% RH.

3.0 RESULTS AND DISCUSSION

Figure 4 depicts the result of the discharge time test. In general, a similar trend of the luminance outputs over the number of cycles was shown by T_{off} of 1 s to 30 s. It can be observed that the luminance values were continuously increasing towards the 25th cycle. The highest luminance value (final reading) was recorded at 2647 cd/m^2 by the shortest T_{off} which was at 1 s, followed by the T_{off} at 10 s (2646 cd/m^2), 20 s (2643 cd/m^2), 30 s (2640 cd/m^2) and 40 s (2633 cd/m^2).

Even though the T_{off} of 1 s to 30 s were generally displayed the same outputs profile, it was noticeable that the gradient of the graph decreased as the T_{off} was becoming longer. Besides, a constant pattern of the luminance outputs can be spotted concerning the switch-off time. The constant outline became more evident as the T_{off} was getting bigger, especially at longest T_{off} of 40 s. Moreover, it was also noted that the final luminance of the OLED was significantly diverged from its initial value, specifically at the shortest T_{off} (1 s).

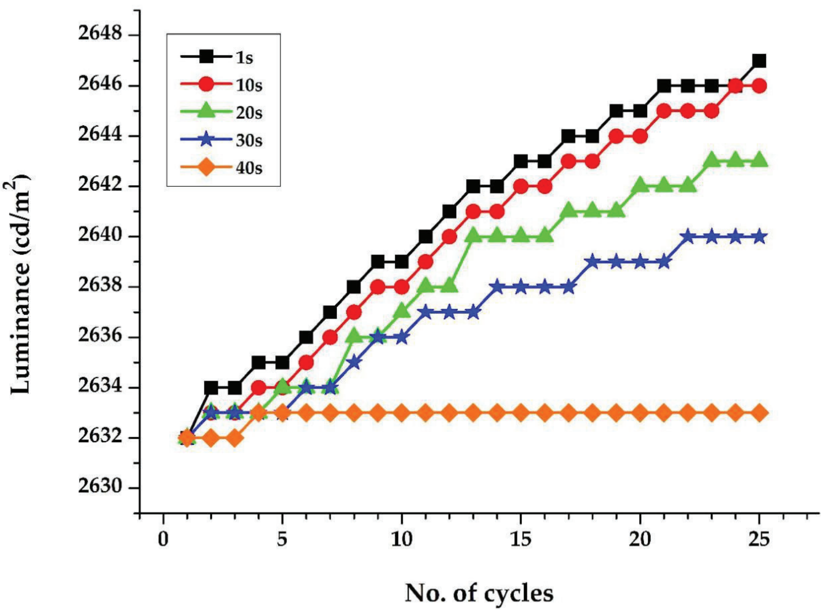

Figure 4: Performance of luminance outputs over cycles at different T_{off}

For comparison purpose, the luminance performance of OLED was summarized in Table 1. It can be observed that the difference in the luminance output (between the final and the initial value) for each T_{off} was decreasing, corresponding to the interval of the switch-off time – the longer the T_{off}, the smaller the discrepancy value. T_{off} of 1 s comprised the largest difference value from its initial luminance reading, which was 15 times larger than the smallest difference of the luminance output, which was at T_{off} of 40 s. From the acquired result, it can also be deduced that the performance of the luminance was extremely dependent on the operational frequency. In this study, the major factor that affected the operational frequency was the switched-off time.

Table 1: Initial and final value of OLED luminance output at different T_{off}

T_{off} (s)	Frequency (Hz)	Luminance output (cd/m^2)		
		1st (Initial cycle)	25th (Final cycle)	Difference value (between final and initial reading)
1	0.500	2632	2647	15
10	0.091	2632	2646	14
20	0.048	2632	2643	11
30	0.032	2632	2640	8
40	0.024	2632	2633	1

Despite the same current density employed throughout the discharge time test, the luminance output of the OLEDs was still increasing. Contrary to the standard practice, the brightness of an OLED is directly proportional to the applied electricity. This occurrence was particularly due to the presence of capacitance effect with respect to the thin structure of the OLED's thickness [29]. Additionally, the obtained result was in a good agreement with the previous studies which had been conducted by Nuo et al. [33] and Liu et al. [34]. From their studies, it can be comprehended that the capacitance effect was primarily crucial at high frequencies.

As the OLED was activated, electrons were injected out of the negative terminal (cathode), through the organic layer and into the positive terminal (anode) of the source. Eventually, the cathode became rich with negatively charge electrons, while the anode was occupied with positively charge holes. Meanwhile, the organic layer operated like a quasi-insulating layer (dielectric material) as the electric current was flowing between the two highly conductive materials. Subsequently, the negatively charged atoms of the organic layer were leaned or shifted towards the opposite pole of the anode plate, caused the atoms within the organic layer to become polarized. During this time, the flow of the electrical current was capable of charging a large parallel capacitance, which allowed the organic layer to store energy for a temporary period [35].

Correspondingly, when the OLED was switched-off, the trapped charge (parasitic capacitance) within the organic layer was discharged by itself. During that state, the organic layer was functioned as the closed-loop path between the electrode plates. Then, the excess charge on one side of the electrode used the closed loop to balance out the charge, as illustrated in Figure 5. The excess electrons from the negative terminal of the OLED was moving towards the positive plate of the device (and vice versa) to allow the charge balance to occur. However, the charge balance process requires some time to ensure the parasitic capacitance can be completely discharged.

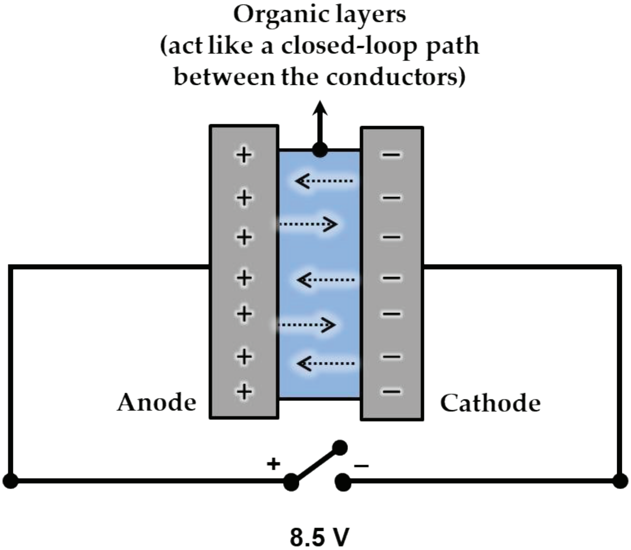

Figure 5: Organic layer acted like a closed-loop path to allow the charge balance process within the OLED device to occur (as indicated by the dashed arrows)

Therefore, when the trapped charge did not have a sufficient time to discharge, it intensified the luminance output as the energy within the OLED had become greater. This mechanism model was consistent with the obtained luminance result, which explained why the T_{off} at 1 s to 30 s exhibited the highest luminance output. Since electrical current had been injected into the OLEDs, it did not have sufficient time to be fully discharged. Thus, the remaining charge increased the luminance output of the OLED at the given constant voltage and current. Conversely, it can be postulated that the OLEDs acquired an efficient time to perform the discharge process at T_{off} 40 s.

Besides that, for the determination of the optimum discharge time, the difference of the luminance output was fixed to be at least 1 cd/m^2 or less. This ensured that the trapped charge within the OLEDs' layer had been discharged, as well as to signify a constancy and uniformity of the luminance output between the initial and final cycle. Apparently, T_{off} at 40 s was able to meet this condition, and hence, it can be stated that the optimum discharge time for the tested OLED can be verified at 40 s.

4.0 CONCLUSION

In summary, this study demonstrated that the performance of the OLED's luminance output was significantly influenced by the duration of discharge time. Even at a constant current density, the shorter T_{off} showed a considerable discrepancy reading of the luminance values as compared to the longer T_{off}. This condition was indubitably affected by the occurrence of unwanted charge due to thin structure of the OLED samples, allowing the organic layer to act as a temporary capacitor and resulting in the change of the luminance outputs of the OLED. Hence, the discharge time of an OLED was vital to be attained to avoid any misleading numbers and information. The collected results from the discharge time test proved the importance of determining the discharge time of an OLED to ensure the accuracy during the valuation process and reliability of the obtained data. This study had successfully determined that discharged time for these particular commercial OLEDs was at 40 s. Future works will cover the effect of discharge time on the luminance output by using multiple layers of OLED along with the statistical study of the obtained results.

ACKNOWLEDGEMENTS

The authors are gratefully acknowledged the Centre for Advanced Research on Energy (CARe), MIMOS Semiconductor (M) Sdn. Bhd. Kuala Lumpur and financial support from Universiti Teknikal Malaysia Melaka and Ministry of Higher Education, Malaysia (MOHE) under PJP HI-Impact Research Grant (PJP/2016/FKM/HI1/S0146), as well as JABIL Circuit Sdn. Bhd. Penang (GLUAR/JABIL/2016/FKM-CARE/I00017).

REFERENCES

[1] C.W. Tang and S.A. VanSlyke, "Organic electroluminescent diodes", *Applied Physics Letter*, vol. 51, no. 12, pp. 913–915, 1987.

[2] M.M. Azrain, M.R. Mansor, S.H.S.M. Fadzullah, G. Omar, D. Sivakumar, L.M. Lim and M.N.A. Nordin, "Analysis of mechanisms responsible for the formation of dark spots in organic light emitting diodes (OLEDs): A review", *Synthetic Metals*, vol. 235, no. 1, pp. 160–175, 2018.

[3] S. Rankel, "Future lighting and the appearance of cities at night: A case study", *Urbani Izziv*, vol. 25, no. 1, pp. 126–141, 2014.

[4] A. De Almeida, B. Santos, B. Paolo and M. Quicheron, "Solid state lighting review – Potential and challenges in Europe", *Renewable and Sustainable Energy Reviews*, vol. 34, no. 6, pp. 30–48, 2014.

[5] J.Y. Tsao, M.H. Crawford, M.E. Coltrin, A.J. Fischer, D.D. Koleske, G.S. Subramania, G.T. Wang, J.J. Wierer and R.F. Karlicek, "Toward smart and ultra-efficient solid-state lighting", *Advanced Optical Materials*, vol. 2, no. 9, pp. 809–836, 2014.

[6] L.J. Sandahl, K.A. Cort and K.L. Gordon, "Solid-state lighting: Early lessons learned on the way to market", Pacific Northwest National Lab (PNNL), Richland, Rep., PNNL-23059, 2014.

[7] P. Pust, P.J. Schmidt and W. Schnick, "A revolution in lighting", *Nature Materials*, vol. 14, no. 5, pp. 454–458, 2015.

[8] D. Chitnis, N. Thejo Kalyani, H.C. Swart and S.J. Dhoble, "Escalating opportunities in the field of lighting", *Renewable and Sustainable Energy Reviews*, vol. 64, no. 10, pp. 727–748, 2016.

[9] J.G. Kassakian, *Assessment of Advanced Solid State Lighting*. Washington: National Academies Press, 2013.

[10] D.J. Gaspar and E. Polikarpov, *OLED Fundamentals*. Florida: CRC Press, 2015.

[11] M. Aleksandrova, "Specifics and challenges to flexible organic light-emitting devices", *Advances in Materials Science and Engineering*, vol. 2016, no. 3, pp. 1–8, 2016.

[12] H. Pang, M. Lech, M.S. Weaver, R. Ma and J.J. Brown, "Thermal behavior and indirect life test of large-area OLED lighting panels", *Journal of Solid State Lighting*, vol. 7, no. 1, pp. 1–13, 2014.

[13] Nanomarkets. (2009). *An Opportunity Analysis for OLED Lighting: 2009 to 2016* [Online]. Available: https://www.oled-info.com/opportunity-analysis-oled-lighting-2009-2016.

[14] T. Junichi, M. Mitsuru, K. Takashi, K. Fujio, Y. Tsutomu and S. Joji, "Development and mass-production of OLED lighting panels with high luminance, long lifetime and high efficiency", *Mitsubishi Heavy Industries Technical Review*, vol. 51, no. 3, pp. 59–65, 2014.

[15] M. Takamura, J. Tanaka, M. Morimoto, K. Mori, K. Hori and M. Musha, "Development of OLED lighting panel with world-class practical performance", *Mitsubishi Heavy Industries Technical Review*, vol. 49, no. 4, pp. 72–78, 2012.

[16] H. Keiichi, S. Joji, T. Makoto, T. Junichi, Y. Tsutomu and T. Yoshitaka, "Development and mass-production of an OLED lighting panel: Most-promising next-generation lighting", *Mitsubishi Heavy Industries Technical Review*, vol. 49, no. 1, pp. 47–53, 2012.

[17] P. V. De Weijer, P.C.P. Bouten, H. Fledderus, R.R. Janssen, S.H.P.M. De Winter and H.B. Akkerman, "Mechanistic study on black and grey spot growth in OLEDs performed on laser-ablated pinholes in the cathode", *Organic Electronics*, vol. 42, pp. 59–65, 2017.

[18] J. Wang, Z. Hu, Z. Zhong, L. Wang, J. Zou, Y. Su, D. Gao, H. Zheng, J. Wang, J. Peng and Y. Cao, "Stressing organic light-emitting diode under constant-brightness driving mode", *Organic Electronics: Physics, Materials, Applications*, vol. 21, no. 6, pp. 192–197, 2015.

[19] H.B. Akkerman, P. van de Weijer, E.J.K. Verstegen, H.H.G. Bolten, S.H.P.M. de Winter and P.A. Rensing, "Sub-micron pinhole detection in the cathode of organic light-emitting diodes", *Organic Electronics*, vol. 44, no. 5, pp. 263–270, 2017.

[20] P. Kaur, V. Karar and N. Marriwala, "Study of effect of environmental factors on organic light emitting diode (OLED) displays: A review", *IOSR Journal of Electronics and Communication Engineering*, vol. 1, no. 1, pp. 84–89, 2016.

[21] C. Féry, B. Racine, D. Vaufrey, H. Doyeux and S. Cinà, "Physical mechanism responsible for the stretched exponential decay behavior of aging organic light-emitting diodes", *Applied Physics Letters*, vol. 87, no. 21, pp. 213502-1–213502-3, 2005.

[22] R. Fan, X. Zhang, Z. Tu, T. Hwang, F. JianHang, P. Lu and M. Jou, "P-195: equivalent lifetime method to improve OLED luminance degradation", *SID Symposium Digest of Technical Papers*, vol. 48, no. 1, pp. 1999–2002, 2017.

[23] T.H. Glisson, *Introduction to Circuit Analysis and Design*. NC: Springer, 2011.

[24] H.S. Kim, J. Kim, C. Chung, J. Lim, J. Jeong, J.H. Joe, J. Park, K.W. Park, H. Oh and J.S. Yoon, "Effects of parasitic capacitance, external resistance, and local stress on the RF performance of the transistors fabricated by standard 65-nm CMOS technologies", *IEEE Transactions on Electron Devices*, vol. 55, no. 10, pp. 2712–2717, 2008.

[25] S. Sangwine, *Electronic Components and Technology*, 3rd Edition. Florida: CRC press, 2007.

[26] M.B.N. Patel and M.M.M. Prajapati, "OLED: A modern display technology", *International Journal of Scientific and Research Publications*, vol. 4, no. 6, pp. 1–5, 2014.

[27] V. Shrotriya and Y. Yang, "Capacitance–voltage characterization of polymer light-emitting diodes", *Journal of Applied Physics*, vol. 97, no. 5, pp. 054504-1–054504-6, 2005.

[28] G. Garcia-Belmonte, H.J. Bolink and J. Bisquert, "Capacitance-voltage characteristics of organic light-emitting diodes varying the cathode metal: Implications for interfacial states", *Physical Review B*, vol. 75, no. 8, pp. 085316-1–085316-8, 2007.

[29] M.N. Tsai, T.C. Chang, P.T. Liu, C.W. Ko, C.J. Chen and K.M. Lo, "Short-diode like diffusion capacitance of organic light emission devices", *Thin Solid Films*, vol. 498, no. 1-2, pp. 244–248. 2006.

[30] V.C. Bender, N.D. Barth, F.B. Mendes, R.A. Pinto, J.M. Alonso and T.B. Marchesan, "Modeling and characterization of organic light-emitting diodes including capacitance effect", *IEEE Transactions on Electron Devices*, vol. 62, no. 10, pp. 3314–3321, 2015.

[31] W. Zhou, C. Zimmermann and C. Jungemann, "Numerical capacitance analysis of single-layer OLEDs based on the master equation", *IEEE Transactions on Electron Devices*, vol. 63, no. 12, pp. 4919–4923, 2016.

[32] International Electrotechnical Commission (IEC). (2017). *Part 6-1: Measuring Methods of Optical and Electro-Optical Parameters (IEC 62341-6-1)* [Online]. Available: https://iecetech.org/In-Store/2017-01/New-edition-of-Standard-for-OLED-displays.

[33] L. Nuo, G. Xin-Dong, X. Zuo-Ti, S. Zheng-Yi, D. Xun-Min and H. Xiao-Yuan, "Negative capacitance in doped bi-layer organic light-emitting devices", *Chinese Physics B*, vol. 20, no. 2, pp. 027306-1–027306-6, 2011.

[34] D. Liu, F. Teng, Z. Xu, S. Yang, S. Quan, Q. He, Y. Wang and X. Xu, "Influence of capacitance effect on alternating-current organic light-emitting diodes", *Solid State Communications*, vol. 137, no. 7, pp. 391–394, 2006.

[35] R.M.A. Dawson, Z. Shen, D.A. Furst, S. Connor, J. Hsu, M.G. Kane, R.G. Stewart, A. Ipri, C.N. King, P.J. Green, R.T. Flegal, S. Pearson, W.A. Barrow, E. Dickey, K. Ping, S. Robinson, C.W. Tang, S. VanSlyke, F. Chen, J. Shi, M.H. Lu and J.C. Sturm, "The impact of the transient response of organic light emitting diodes on the design of active matrix OLED displays", in International Electron Devices Meeting, San Francisco, CA, USA, 1998, pp. 875–878.