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Low-Frequency Noise Measurement and Analysis in Organic Light-Emitting Diodes

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***Abstract*—Low-frequency noise characteristics of organic light-emitting diodes are investigated. Two noise components were found in experimental low-frequency noise records, namely: 1) 1/f Gaussian noise from device bulk materials and 2) an excessive frequency-related part of noise related to device interfaces or defects and traps. 1/f noise is said to be related to carrier mobility. Degradation, especially photo-oxidation of the electroluminescence polymer, is a possible reason that affects carrier mobility. The excessive part of noise is believed to be related to the carrier numbers and could come from the interface deterioration, defects and traps generation and furnish. The excessive part of noise increases much faster during device stress. This shows that the degradation related interface defects and traps is much faster.**

***Index Terms*—Low-frequency noise, organic light-emitting diode (OLED), 1/f noise.**

I. Introduction

THE BRIGHTNESS and efficiency of organic light-emitting diodes (OLEDs) are now considered comparable to those of light-emitting diodes (LEDs) based on inorganic materials and have a lot of advantages over traditional liquid-crystal display (LCD) [1], [2]; however, long-term stability remains one of the critical issues hindering practical applications.

Conventional techniques for studying device degradation are mainly based on lifetime tests under accelerated stress conditions, and they are well suited for collecting statistical information on the expected lifetime of a given set of devices. Low-frequency noise is a sensitive diagnostic tool to examine the internal mechanisms of electrical devices [3], [4]. For example, it has been shown that devices with identical current–voltage (I–V) behavior can exhibit very different low-frequency noise characteristics. This is primarily because the I–V behavior represents a macroscopic description of the device characteristics, whereas low-frequency noise is a sensitive probe of defects, nonuniformities, surface velocity fluctuations, etc., due to incomplete bonding or defect sites at surfaces or interfaces [5]. Furthermore, a correlation between the device morphological changes that occurred during the degradation process and the low-frequency noise changes is observed. This suggests that sampling of noise during device operation can be used as a very efficient tool to obtain device physics information and explore the inner device degradation mechanism of LEDs in real-life applications, which could not be easily obtained by macroscopic method [6].

There have been several publications dealing with low-frequency noise in both semiconductor materials and devices. However, there are relatively very few studies on the low-frequency noise of OLEDs. In this letter, a low-frequency voltage noise investigation across OLEDs was reported.

II. Experiments

Indium–tin–oxide (ITO)-coated glass with a sheet resistance of 20 Ω/sq was used as a substrate for OLED device fabrication. The routine cleaning procedure includes sonication in acetone and methanol followed by oxygen plasma treatment. A naphthyl-substituted benzidine derivative (NPB) hole-transport layer measuring 75 nm and an aluminum tris (8-hydroxyquinoline) $(\mathrm{Alq_3})$ electroluminescence (EL) layer measuring 75 nm are deposited in high-vacuum 2×10^{-5} Pa. A 5 Å lithium fluoride (LiF) and a 200-nm-thick aluminum (Al) are deposited as cathode.

The device is kept in a shielded metal box and powered by a constant current supply, which is powered by batteries. The photodiode is also put in the metal box for light detection. The voltage across the OLED and current from the photodiode were measured using a National Instrument PXI-4070 digital multimeter. Both of the noises from the OLED voltage and from the photodiode current were measured using a National Instrument PXI-5122 two-channel high-performance high-speed digitizer, which can perform both spectrum and time-domain analysis. The optical noise of the OLED device is subjected to another publication. A verification of the system noise measurement is done using a commercial metal-film resistor.

III. Results and Discussion

Fig. 1 shows the frequency dependence of the noise power spectrum density (PSD) $\mathrm{Sv}(f)$ at five different stress times of 4 min, 12, 35, 56, and 74 h. The device is driven under a constant current of $I = 2$ mA, which corresponds to a current density of 0.05 $\mathrm{A \cdot cm^{-2}}$ at a room temperature of $T = 295$ K in dark shielded metal box without encapsulation. The device lifetime has been continuously tested for about 80 h. The inset shows device lifetime curves. With increasing stress time, the luminescence is decreasing and driving voltage

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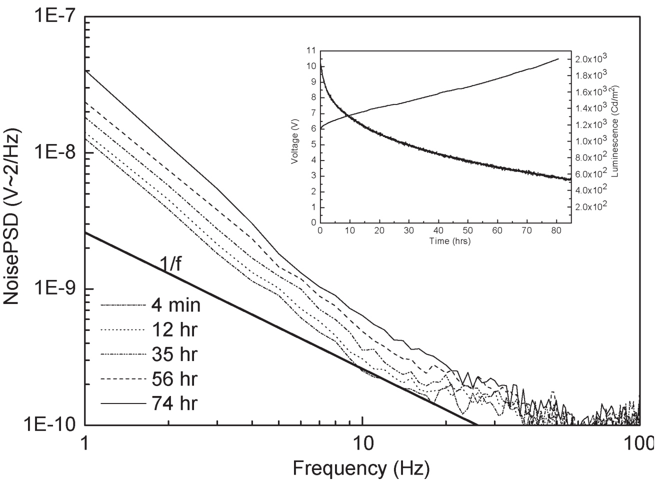

Fig. 1. Frequency dependence of PSD Sv(f) at five different stress time of 4 min, 12 h, 35 h, 56 h, and 74 h. The inset shows device lifetime curves (voltage versus time and luminescence versus time).

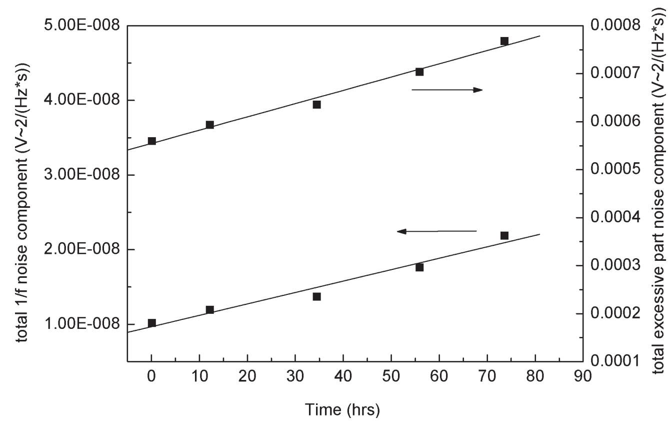

Fig. 2. Total 1/f noise component of $S_{v,1/\mathrm{f}}$ and total excessive part noise Sv,$_I$ component for the five respective stressing times indicated in Fig. 1. The increase rate of the excessive part of noise is 7.68×10^{-10} V^2/Hz · s, whereas that of the 1/f noise is 4.24×10^{-14} V^2/Hz · s.

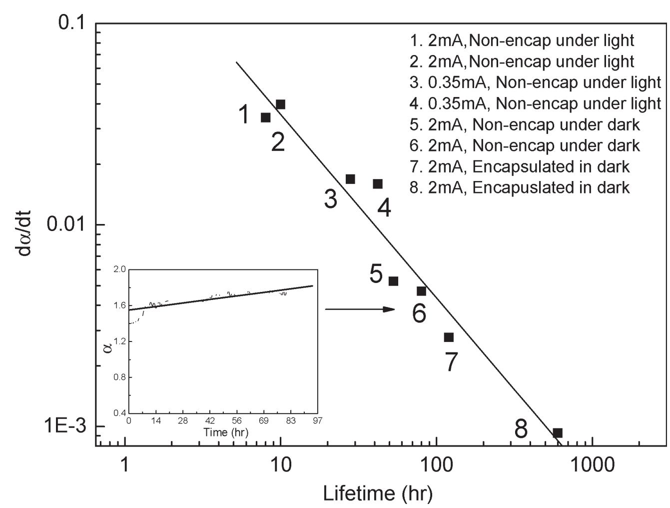

Fig. 3. Frequency exponent α change rate versus device lifetime. Inset: frequency exponent α versus stress time for sample point no. 6.

is increasing. As shown in Fig. 1, all the Sv(f)s show generic 1/f$^{\alpha}$ behavior. The 1/f curve is also shown in the figure (solid line) for comparison. It can be observed that the absolute value of the low-frequency noise slope indicated in Fig. 1 in log scale is the frequency exponent α in Hooge's equation. The calculated slope α is from 1.4 to 1.8. From the figure, it shows that with increasing stress time, the total noise and noise slope are increasing. This phenomenon was observed in every device measured, and it means that as a device degrades, the total low-frequency noise is increasing.

1/f noise is found in all conductors, and their spectral intensity is of the form 1/f$^{\alpha}$ with α close to unity. The contribution of the total noise of the OLED structure under test is a total contribution from bulk of EL materials, bulk of metal contacts, the interfaces, and other sources such as traps and defects, etc. If the 1/f noise is from bulk of materials and metal, the slope should be strictly unity according to Hooge's theory [7]. Therefore, the excessive part of the noise, which causes the low-frequency noise slope is not unity, must be from the interfaces and other resources. Assume the total spectral density of the low-frequency noise observed in the studied devices can be described in general as

$$\mathrm{Sv}(f) = S_{v,1/\mathrm{f}} + \mathrm{Sv},_e$$

where Sv(f) is the total PSD, $S_{v,1/\mathrm{f}}$ indicates the total PSD of 1/f noise, and Sv,$_e$ shows the total PSD of the excessive part of noise from the interfaces. In order to analyze and compare the strength of 1/f noise and the excessive part of noise, an extraction of 1/f noise and the excessive noise is done through spectrum separation. Fig. 2 shows the total 1/f noise component of $S_{v,1/\mathrm{f}}$ and the total Sv,$_e$ component for the five stressing times indicated in Fig. 1. As shown in Fig. 2, both of the 1/f noise and excessive noise are increasing as stress time increases. The excessive part of noise increases much faster with a slope of 7.68×10^{-10} V^2/Hz · s compared with the 1/f noise, which has an increasing rate of 4.24×10^{-14} V^2/Hz · s.

It can be observed that the absolute value of the low-frequency noise slope indicated in Fig. 1 in log scale is the frequency exponent α in Hooge's equation. α can be obtained for each 1/f$^{\alpha}$ noise PSD at each specific time. The inset of Fig. 3 plots the frequency exponent α at every specific time. $d\alpha/dt$ is obtained by linear fitting the plot in the inset of Fig. 3. A set of NPB/Alq$_3$ OLED devices with the same structure and process are fabricated and subjected to the lifetime test under either light or dark. Devices with a lifetime larger than 100 h are encapsulated devices. $d\alpha/dt$ versus the different devices' corresponding lifetimes are then shown in Fig. 3. It shows that the slower the slope increases, the longer the device lifetime; the change trend follows the exponential rule.

Hooge proposed that 1/f noise is associated with carrier mobility [7]. Therefore, one explanation for the increase of the 1/f noise of OLED during its degradation is that the mobility of carriers inside the OLED decreases. Hence, high mobility of carriers produces less noise, and low mobility of carriers produces more noise. This is also reasonable in the case of EL materials because electrons move in EL materials by hopping. Low mobility makes electrons hard to hop forward and make more noise [8]. One physical mechanism associated with carrier mobility is the degradation of EL materials. It is well known that the critical drawback of the EL materials is the rapid rate of photo-oxidation under ambient conditions [9], [10]. The oxygen precipitate can act as scattering centers to cause the change of mobility of the charge carriers, which in all cases cause the carrier mobility decreases, further degrading device performance and ultimately limiting device lifetime. The mobility related to scattering centers such as oxygen precipitate is also reported in other papers [11].

The excessive part of low-frequency noise, which leads to an abnormally high level of 1/f noise, can be explained by the fluctuations in the number of charge carriers. Song *et al.* [12] used the tunneling model with a direct application of McWhorter's potential [13] fluctuation mechanism and explained the higher amplitude of noise PSD in the low-frequency range. They suggested that the energy barriers resulting from abundant defects should cause fluctuations in the number of charge carriers, which would lead to an abnormally high level of 1/f noise. In the OLEDs, the degradation is under extensive studies and largely attributed to the formation of nonemissive spots caused by the degradation of the EL materials, the delamination at the cathode interface, cathode oxidation, and electrochemical reactions at the organic/electrode interfaces. The interface deterioration has been proved to play an important role in the device degradation process [14], which definitely increases and fluctuates the energy barriers and causes the fluctuations in the number of charge carriers. The other possible reasons, which also lead to the fluctuations of the carrier number, are widely existing material defects and flaws. The EL material defects could come from the synthesis and purification process, etc., and could decrease the carrier injections and cause the much-increased low-frequency noise level.

Comparing the two aforementioned low-frequency noise mechanisms, as shown in Figs. 2 and 3, a higher increase rate of frequency exponent $d\alpha/dt$ shows that the faster the noise increase, the shorter the device lifetime and that the excessive part of the noise increases much faster than the 1/f noise part. The low-frequency noise analysis hints that in order to increase the device lifetime, measures have to be adopted to suppress the low-frequency noise level and its increase rate. The excessive part of noise, which increased faster than the 1/f noise part, shows that carrier-number-increase-related interface or defected degradation increased much faster than mobility-decrease-related bulk degradation during device lifetime stress.

IV. Conclusion

Low-frequency noise characteristics of OLEDs are investigated. Spectrum extraction techniques are used to obtain two different noise spectra. Two noise components were found in experimental noise records, namely: 1) 1/f Gaussian noise from device bulk materials and 2) an excessive frequency-related part of noise related to device interfaces or defects and traps. 1/f noise is said to be related to carrier mobility. Degradation, especially photo-oxidation of the EL active material, is a possible reason that affects carrier mobility. The excessive part of noise is believed to be related to the carrier numbers, which the fluctuation could be from, the interface deterioration, and defects and traps generation and furnish. The excessive part noise increase much faster during device stress, which shows that the degradation related to interface, defects and traps is much faster. These two noises have different physical origins in LEDs. The shorter the lifetime, the faster the noise slope increases.

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