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Transient characteristics of organic light-emitting diodes with efficient energy transfer in emitting material

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ABSTRACT

We have investigated the combination effect of host–guest materials in an emitting layer on the transient property of an organic light-emitting diode (OLED). We found that an efficient energy transfer owing to the large overlap between the photoluminescence spectrum of host material and the absorption spectrum of guest material was an important factor to improve the response speed of the OLED. As a result, the rise time of optical response was mainly affected by the combination of host–guest materials, and it increased using the optimal guest material, 1,4-bis[2-[4-*N*,*N*-di(*p*-tolyl)amino]phenyl]vinyl]benzene (DSB). A maximum −3 dB cutoff frequency of 15.8 MHz was achieved for an OLED with DSB as a guest material.

1. Introduction

Organic light-emitting diodes (OLEDs) have attracted great interest for flat-panel display and lighting applications owing to their possibility of printable devices with a low fabrication cost [1,2]. The high external quantum efficiency was achieved using novel organic emitting materials with the high internal quantum efficiency [3], the improvement in carrier balance in an emitting layer (EML) [4], and the efficient carrier injection from a metal cathode to an adjacent organic layer [5,6]. In addition, the efficient carrier recombination in an EML is necessary to improve the luminescence efficiency, and the combination of host–guest materials is one of the most important techniques to avoid concentration quenching, resulting in the realization of high device performance [7–9].

Promising results have been obtained indicating a potential application of OLEDs as light sources for optical communication systems owing to their fast electro-optical conversion speed [10,11]. The merits of an organic light source are their large emitting area, flexibility, and low fabrication cost. In particular, a large emitting area, which realizes easy alignment between an organic light source and an organic photo diode, is difficult to be achieved utilizing inorganic materials. However, the electro-optical conversion speed of an OLED is lower than that of a conventional semiconductor light source, and the low response speed limits their application to optical communications.

A transient characteristic of an OLED is determined by combining various elementary electrochemical processes, including charge-carrier injection into organic layers from two electrodes (transparent anode and metal cathode), charge-carrier transportation in organic layers, buildup of space charges, formation of an excited state, and radiation decay from an excited state. Until now, several factors that affect transient properties of OLEDs have already been investigated, such as the capacitance determined by device area [12,13], the fluorescence lifetime of light-emitting materials [14], the energy gap at the metal–organic interface [15], and the carrier mobility of electron/hole transport materials [16–18]. The reported −3 dB cutoff frequency was approximately 25 MHz with a small circular area of 300 μm diameter at a high applied voltage of 15 V [19]. However, the response speed is not high enough to transport a high resolution movie file at a short time, and further improvement in the response speed has been required for practical application.

In this paper, we investigated the combination of host–guest materials in an EML to understand the carrier dynamics in a stacked organic multilayer structure. The transient characteristic of optical response was estimated while applying pulse and sine wave voltages. We used three guest materials, 1,4-bis[2-[4-*N*,*N*-di(*p*-tolyl)amino]phenyl]vinyl]benzene (DSB), 4,4-bis(2,2-ditolylvinyl)biphenyl (DPVBi), and 4,4′-(bis(9-ethyl-3-carbazovinylene)-1,1′-biphenyl (BCzVBi), respectively.

2. Experimental

To ingest the transient property of OLEDs with different combinations of host–guest materials, we fabricated three devices, referred as devices A (DSB), B (DPBVi), and C (BCzBVi). The cross sectional view of these devices is described in Fig. 1. At first, an indium tin oxide (ITO) anode with the thickness of 150 nm was sputtered on the top of the glass substrate, and the ITO-coated glass substrate was cleaned in deionized water, detergent, and isopropyl alcohol sequentially under ultrasonic waves.

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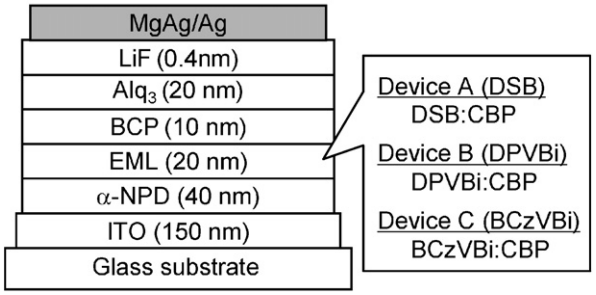

Fig. 1. Cross sectional view of devices A, B, and C with different guest materials.

Next, the prepared glass substrate was treated with oxygen plasma for 5 min. Finally, organic layers and the MgAg (9:1 w/w)/Ag cathode were thermal evaporated at a base pressure of below 5.0×10^{-6} Torr. Each organic layer consisted of4,4′-bis[*N*-(1-napthyl)-*N*-phenyl-amino]-biphenyl (α-NPD) as a hole transport layer, bathocuproine (BCP) as a hole block layer, and tris(8-hydroxyquinoline)aluminum (Alq_3) as an electron transport layer, respectively. Three organic emitting materials were chosen as DSB (device A), DPVBi (device B), and BCzVBi (device C) doped with 4, 4′-bis(9-dicarbazolyl)-2, 2′-biphenyl (CBP) at 0.5 wt.%, respectively. We estimated the concentration of host–guest materials by the evaporation rate of each material. The device structure was α-NPD 40 nm/EML 20 nm/BCP 10 nm/Alq_3 20 nm/LiF 0.4 nm/MgAg 100 nm/Ag 50 nm. Emitting areas of all the devices were fixed at 1 mm^2.

We measured photoluminescence (PL) and absorption spectra of organic neat films using a spectrofluorometer (JASCO, FP-750) and a spectrometer (Hitachi, U3200), respectively. In addition, current density–voltage (*J*–*V*) and current efficiency–current density characteristics of devices were obtained using an OLED luminance efficiency measurement system (Precise Gauges, EL1003).

Rise and decay times of output electroluminescence (EL) intensity were measured while applying a pulse voltage with a width of 1 μs to investigate the transient property. The bias and pulse voltages were applied to the device using a function generator (Agilent, HP81110A) and a DC power supply (ISO-TECH, IPS-3610D), respectively. Then, generated light was received using an avalanche photo diode (APD), and a time-resolved output power was measured with an oscilloscope (Yokogawa Electric, DL-1740). The rise and decay times were defined as the times required for the optical response to change from 10 to 90% of the maximum EL intensity. The cutoff frequency of experimental setup was over 500 MHz, and the time constant of experimental setup had less influence on the optical waveform of the OLED.

We also measured the EL intensity as a function of the frequency of an applied sine wave voltage. The sine wave and bias voltages were applied to OLEDs using a programmable FM/AM standard signal generator (KENWOOD, SG-7200) and a DC power supply, respectively. The output EL intensity was observed using an APD and an oscilloscope. The frequency dependence of EL intensity was measured by changing the frequency of the sine wave voltage from 100 kHz to 10 MHz.

3. Results and discussion

Fig. 2 shows the absorption coefficients of neat thin films of guest materials (DSB, DPVBi, and BCzVBi) and the PL spectrum of the CBP film, which was used as the host material in the EML. The peak wavelength of PL spectrum of CBP was 411 nm, and the PL intensity rapidly decreased in both shorter and longer wavelengths. The guest material had a peculiar absorption band at the violet wavelength region. The peak wavelengths of absorption spectra of DSB, DPVBi, and BCzVBi were 418, 354, and 372 nm, respectively. Based on previous researches, the energy transfer efficiency of dye-doped OLEDs depends on the overlap integral of the emission spectrum of a host material and the absorption spectrum of a guest material. [20,21]. The measured spectral overlap was different from each combination, and the largest value was achieved using DSB as a guest material. Therefore, efficient Förster energy transfer from the host material to the guest material is considered to be realized in the case of DSB doped CBP.

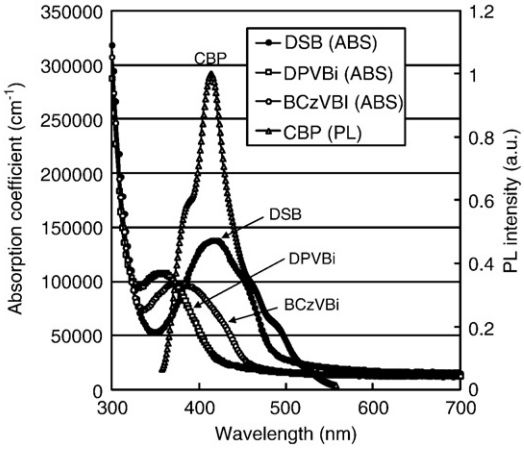

Fig. 2. Absorption spectra of guest materials (DSB, DPVBi, and BCzVBi) and the PL spectrum of CBP.

J–*V* characteristics of devices A (DSB), B (DPVBi), and C (BCzVBi) are shown in Fig. 3(a). Almost the same trends were obtained for all the devices because of the same device structure, such as thicknesses and energy levels of organic layer except for the guest material. Fig. 3(b) shows current efficiency–current density characteristics of the three devices. As shown in Fig. 3(b), the OLED with DSB exhibited higher current efficiency (7.3 cd/A at the current density of 1 mA/cm^2) than other devices (0.9 and 1.5 cd/A at 1 mA/cm^2 for devices B (DPVBi) and C (BCzVBi). This tendency indicates that efficient energy transfer from

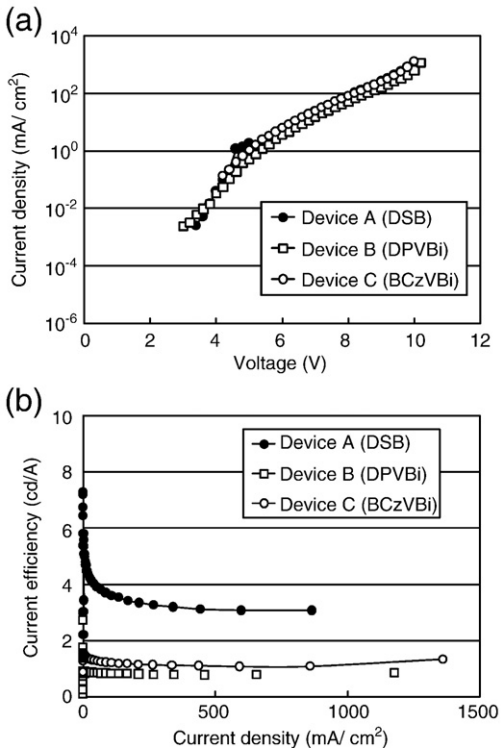

Fig. 3. (a) Current density–voltage and (b) current efficiency–current density characteristics of devices, of which DSB, DPVBi, and BCzVBi were used as guest materials in the EML, respectively.