Organic Light-Emitting Diode for Optical Interconnect

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We demonstrate the fast response and high directivity of microcavity organic light-emitting diodes (MOLEDs) for optical interconnect applications. A MOLED can be fabricated onto a flexible substrate with printing or low-temperature evaporation processes. Therefore, we have developed a novel flexible optical interconnect with a MOLED light source. This optical interconnect is expected to be a useful device because this device can be assembled in a small area due to its thickness and flexibility. In the case of light source for transmission, though an OLED has several characteristics, they are not enough for practical applications. In this paper, we show the improvement on current efficiency, directional property and transmission speed by utilizing a microcavity structure. The maximum cutoff frequency and the coupling efficiency are 7 MHz and 83 % with an optical waveguide having a 0.5 numerical aperture, respectively.

1. Introduction

In recent times, a transmission speed has increased rapidly in electronic equipment such as flexible printed circuit and a coaxial cable, in which an electronic interconnect is used. However, currently a transmission speed has almost reached the theoretical limit of electronic interconnect. Therefore, an optical interconnect has been required as a substitute for electronic interconnect. An optical interconnect is desirable for realizing a high transmission speed, which is difficult to be achieved with an electronic interconnect. Recently, there have been a number of reports on an optical interconnect, which consists of a vertical cavity surface-emitting laser (VCSEL) and a photo-diode (PD). Reported optical interconnects can realize more than gigabits per second (Gbps) transmission speed [1) 2)].

Applications of this optical interconnect have been limited by several intrinsic problems as follows: One problem is a high assembly cost because high accuracy alignment of a VCSEL and a PD is necessary to connect an optical waveguide, which guides a signal light from a VCSEL into a PD. The other problem is the thickness of the optical interconnect. A VCSEL and a PD are fabricated onto a semiconductor substrate, and then they are assembled with solder or Ag paste onto another substrate. Thus, thin optical interconnect is difficult to realize.

One approach to realizing low-cost and thin optical interconnect is the use of an organic light-emitting diode (OLED), an organic photo-diode (OPD), and a connected polymer optical waveguide (Fig.1). These devices can be fabricated with a printing method or a low-temperature evaporation process onto a flexible substrate. This novel optical interconnect is considered to have broad applications because of the flexibility, the thinness and the low-cost fabrication process requirements that further provide distinct advantages over the normal optical interconnect with a VCSEL and a PD.

Recently, several reports showed high-speed response OLEDs [3) 4)]. By utilizing a short fluorescence lifetime light-emitting layer (EML), more than 100 megabits per second (Mbps) transmission speed was demonstrated [4)]. However, the reported transmission speed is not always sufficient. It has been recognized that several hundreds Mbps or Gbps of transmission speed is desirable to correspond to the expansion of the application of electronic equipment.

In this paper, we show current density versus voltage characteristics and electroluminescence (EL)

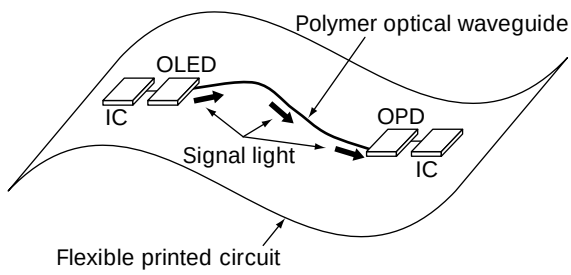

Fig.1. Schematic configuration of the optical interconnect with the organic light-emitting diode and the organic photo-diode.

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spectra of a microcavity organic-light emitting diode (MOLED). Furthermore, by utilizing a microcavity structure, a coupling efficiency with a polymer optical waveguide and a transient response of OLEDs are evaluated for the possibility to realizing an OLED light source.

2. Principles of MOLED

A normal OLED consists of an organic EML between two electrodes. One of the electrodes is transparent to take a light out of the EML. On the contrary, a MOLED is fabricated on a dielectric multilayer filter coated substrate, as shown in Fig. 2. The emitted light from the EML is reflected at the dielectric multilayer filter and a metal cathode, respectively. If the reflectivity of the dielectric multilayer filter is lower than that of the metal cathode, only resonant wavelength is taken through the dielectric multilayer filter and a glass substrate. There have been many studies of directional characteristics in MOLEDs, and then it is well known that the directivity is improved as compared with the non-cavity OLED [5) 6) 7)]. Therefore, high coupling efficiency with a polymer optical waveguide will be achieved by utilizing a microcavity structure. And it is surmised that a transmission speed can be improved with a cavity structure in the same way as in a semiconductor laser.

3. Experimental

First, we prepared the dielectric multilayer filter, which consists of four pairs of SiO_2 and Ta_2O_5, and an indium tin oxide (ITO) anode onto a glass substrate. The dielectric multilayer filter and 100 nm thickness of ITO layer are deposited with electron beam deposition and RF sputtering methods, respectively. Thicknesses of SiO_2 and Ta_2O_5 layers are set to be equal to quarter optical length of the peak emission; they are 86.32 nm and 56.85 nm, respectively. The reflectivity of the fabricated dielectric multilayer filter is 80.0 % and 75.5 % at the wavelength of 510 nm and 560 nm, respectively. This wavelength is the peak emission of OLEDs with coumarin 6 and rubrene doped Alq_3 as the EML, respectively. Then, prepared glass substrates were cleaned in deionized water, detergent and isopropyl alcohol sequentially under ultrasonic waves, and treated with 50 W oxygen plasma before use.

Lastly organic layers and a cathode were evaporated with a vacuum deposition system at a base pressure of below 5.0×10^{-6} Torr. The organic multilayer consists of 4,4'-bis[N-(1-napthyl)-N-phenyl-amino]-biphenyl (α-NPD) as a hole transport layer (HTL), tris (8-hydroxyquinoline) aluminum (Alq_3) doped with 0.4- wt% coumarin 6 or rubrene as an EML, Alq_3 as an electron transport layer (ETL), LiF as an electron injection layer (EIL), and MgAg (9:1 mol. ratio)

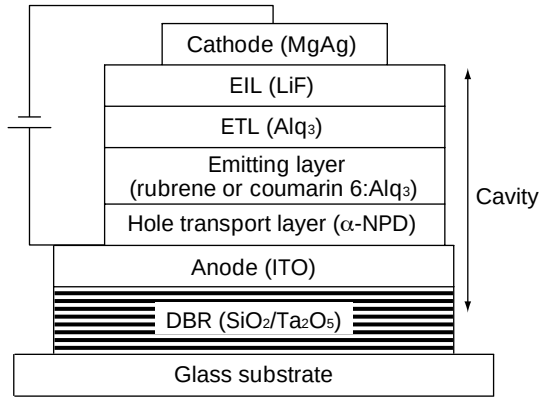

Fig.2. Cross-sectional view of the microcavity organic-light emitting diode.

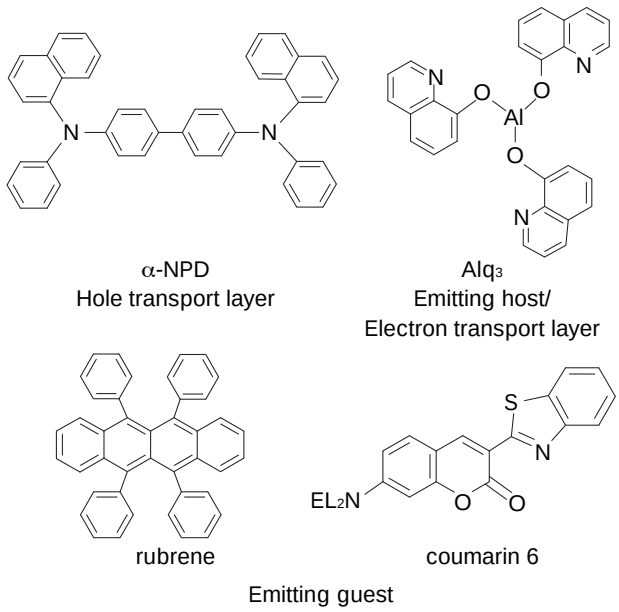

Fig.3. Molecular structures of organic materials.

as a cathode. Thicknesses of each layers are determined as follows:

(a) ITO 100 nm/α-NPD 40 nm/rubrene: Alq_3 (0.4-wt.%) 20 nm/Alq_3 40 nm/LiF 0.4 nm/MgAg 150 nm

(b) ITO 100 nm/α-NPD 28 nm/coumarin 6: Alq_3 (0.4-wt.%) 20 nm/Alq_3 22 nm/LiF 0.4 nm/MgAg 150 nm

Figure 3 shows molecular structures of organic materials. Deposition rates were set to range from 0.08 to 0.12 nm/s for the ETL and the HTL, 0.01 to 0.02 nm/s for the EIL, and 5.0 nm/s for the EML and the cathode. An active area is 1×1 mm^2.

4. Results and Discussion

4.1. Current density-luminance characteristic

We measured current density-voltage-luminance

characteristics with a source measure unit (HP4140B, Hewlett-Packard) and a luminance color meter (BM-7, TOPCON). The color meter was placed on a normal of the test device to measure a front luminance.

Figure 4 (a) and (b) shows current density-luminance characteristics of OLEDs with rubrene and coumarin 6 doped Alq_3 as the EML, respectively. As shown in Fig. 4 (a), the luminance of the MOLED is nearly equal to that of the non-cavity OLED. The current efficiency of the MOLED is 9.0 cd/A, which is 8 % more than the non-cavity OLED. On the contrary, the current efficiency of the OLED with coumarin 6 doped Alq_3 as the EML is substantially small by utilizing the microcavity structure. The current efficiency of the MOLED is 3.3 cd/A, whereas it is 8.9 cd/A for the non-cavity OLED. The difference between rubrene and coumarin 6 can be explained by an absorption of coumarin 6 doped Alq_3 layer. The coumarin 6 doped Alq_3 film has absorption at the wavelength of 510 nm, which is the resonance wavelength of the MOLED. Therefore, the light generated from the EML is absorbed in the EML, and the current efficiency is decreased.

4.2. EL spectrum

EL spectra were also measured with a luminance color meter. EL spectra of OLEDs with (a) rubrene and (b) coumarin 6 doped Alq_3 as the EMLs are summarized in Fig. 5. The non-cavity OLED has broad EL spectrum about a full width half maximum (FWHM) ranged from 50 to 100 nm. However, the spectral width is narrowed with a microcavity structure, the FWHM of EL spectra are 12.1 and 10.1 nm for OLEDs with rubrene and coumarin 6 doped Alq_3 as the EML, respectively. Narrow spectrum is suitable for a wavelength division multiplexing system, which can realize a high transmission speed.

4.3. Coupling efficiency with a polymer optical waveguide

An angular dependence on an EL intensity was measured with a color meter by tilting the test device. Figure 6 shows the angular dependence of the EL intensity to estimate a coupling efficiency between the OLED and a polymer optical waveguide. High coupling efficiency is important to deliver a signal light from an OLED to an OPD.

In both cases of OLEDs with rubrene and coumarin 6 doped Alq_3 as the EML, the directional characteristics are improved with the microcavity structure, and the FWHM of two MOLED devices becomes 50 degrees.

We calculated the coupling efficiency between the MOLED device and an optical waveguide having a 0.5

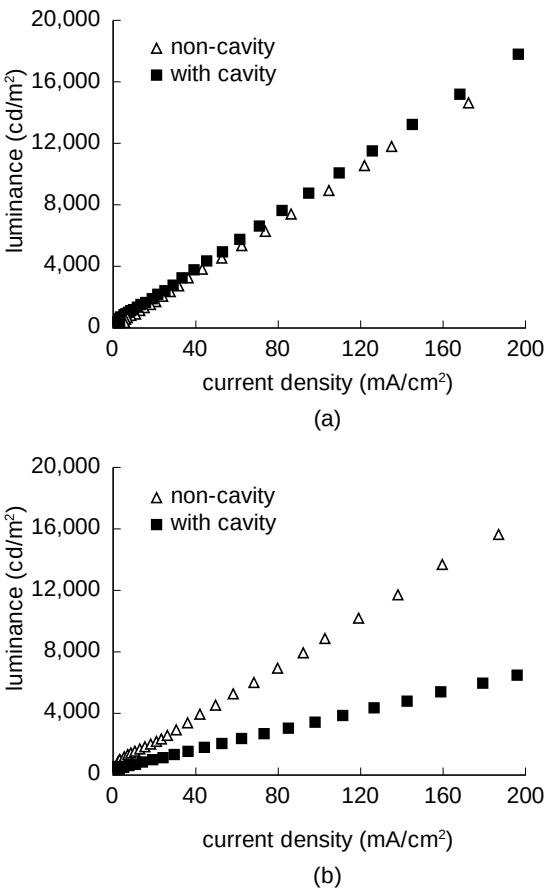

Fig.4. Current density-luminance characteristics of OLEDs with (a) rubrene and (b) coumarin 6 doped Alq_3 EMLs.

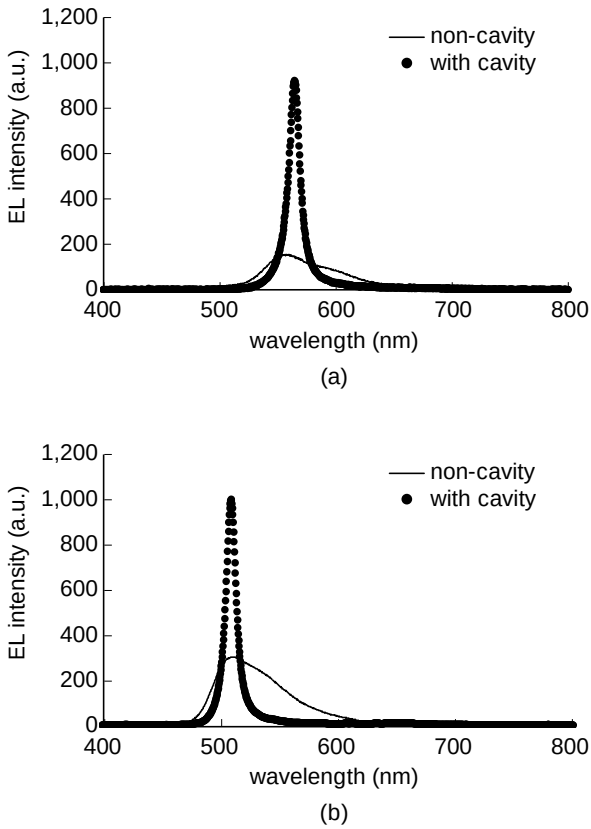

Fig.5. EL spectra of non-cavity OLEDs and the MOLEDs with (a) rubrene and (b) coumarin 6 doped Alq_3 EMLs.

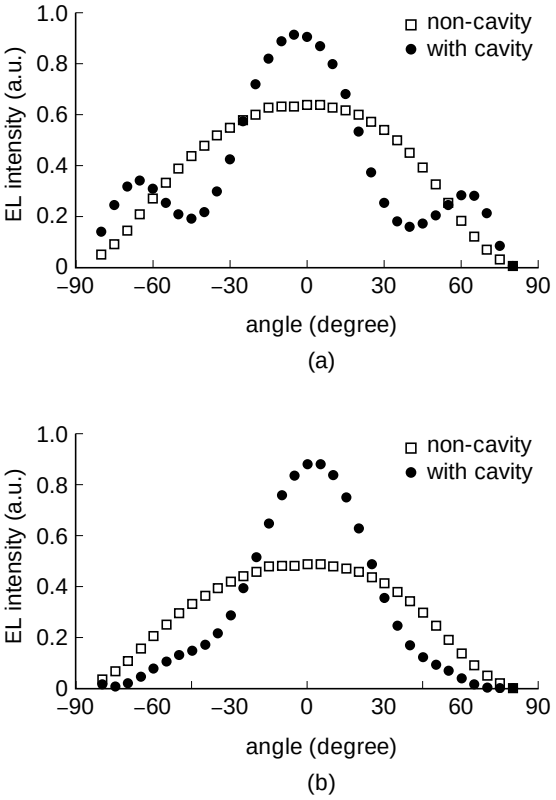

Fig.6. The angular dependence of electroluminescence intensity. EMLs are (a) coumarin 6 doped Alq_3 and (b) rubrene, respectively.

numerical aperture. The coupling efficiency is 68 % and 83 % for MOLEDs with the rubrene and coumarin 6 doped Alq_3 as the EML, and the enhancement of the coupling efficiency is 1.2 and 1.4, respectively. As shown in Fig. 6 (a), the OLEDs with coumarin 6 doped Alq_3 as the EML has the second peak at the larger tilting angles. Therefore, the coupling efficiency of the OLEDs with coumarin 6 doped Alq_3 as the EML is lower than that of the OLEDs with rubrene doped Alq_3 as the EML. The second peak is excited by the longer cavity length at a larger tilting angle [5], and the center wavelength of the second peak is 630 nm. In order to improve the coupling efficiency, the light confinement structure is necessary with low refractive index region surrounded with the EML and only then resonance wavelength will be emitted.

4.4. Dependence of EL intensity on frequency of sine-wave voltage

The highly response speed of EL intensity was measured by applying sine-wave voltage with programmable FM/AM standard signal generator (SG-7200, KENWOOD). The transient EL intensity was observed by using an avalanche photo-diode

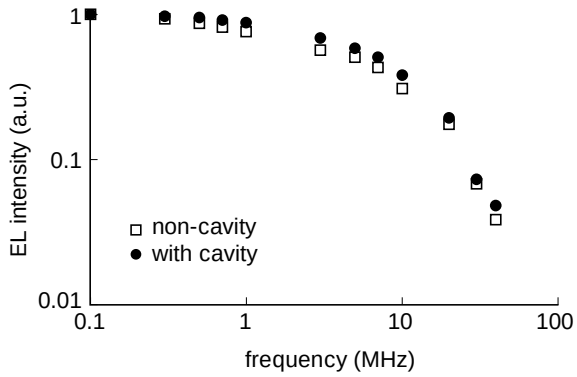

Fig.7. The relationship between the electroluminescence intensity and the frequency of applied sine-wave voltage.

(Hamamatsu Photonics). We show the logarithmic plot of the EL intensity versus the frequency of the applied sine-wave voltage in Fig. 7, where the amplitude of sine-wave and bias voltages are set at 7 and 5 V, respectively. The dependence of the ferquency on the EL intensity is shifted to the high frequency region. This result indicates that the high transmission speed can be achieved with the microcavity structure.

The reason for the limit of the transmission speed is considered to be a capacitance of organic layers [4], a carrier mobility of the ETL / HTL and a fluorescence lifetime of the EML [3]. We examine the optimization of these parameters for the rapid improvement on transmission speed of the MOLED.

5. Conclusion

We examine the possibility of the OLED light source for an optical interconnect. By utilizing the cavity structure of the OLED with rubrene doped Alq_3 as the EML, we show the improvement on the current efficiency, the EL spectrum, the coupling efficiency with the polymer optical waveguide, and transmission speed. The MOLED is a suitable device for an optical interconnect.

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