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White light-emitting LED using electrospun Alq3/P3BT composite microfibers

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ABSTRACT

We prepared a white light-emitting LED by electrospinning small organic molecules (Alq3) and polymer (P3BT) composite microfibers directly onto a blue LED. The formation of the composite microfiber was optically characterized using the photoluminescence and Raman spectroscopy at the single strand level. We found that the 23:1 weight ratio of Alq3 and P3BT produced optimized white emission when combined with the intrinsic blue emission from the LED due to the fluorescence resonance energy transfer from the Alq3 to the P3BT. The environmentally friendly Alq3/P3BT organic composite microfibers efficiently demonstrated the photo conversion of blue LED into pure white LED.

1. Introduction

White light-emitting diodes (WLEDs) are of great interest because they can be used in full-color flat-panel displays with color filters, backlight panels, and as solid-state lighting sources [1–7]. WLEDs deliver very high luminous efficiency compared to conventional incandescent sources [1,2,6]. One of the popular approaches of achieving white light is using a combination of red, green and blue (RGB) LEDs, which makes it possible to tune appropriate output levels in the visible light spectrum [7]. An alternative approach is to use a blue or UV LED to excite one or more phosphor or organic molecule wavelength converters [2,6,7]. Organic molecules, including dyes and other small molecules or some polymers, are highly fluorescent with broad photoluminescence (PL) spectra, which are the key properties to create an efficient white light-emitting diode compared to a phosphor-based LED [1–3]. Pure white light sources using organic molecules have been designed by considering the absorption and emission spectra as well as the fluorescence resonance energy transfer (FRET) when using multiple chromophores [1,2,4]. However, one of the significant draw backs of many organic dye molecules is that they have reduced long-term stability due to bleaching, where the bleaching action of dye is sensitive to the large absorption wavelength range [8]. This kind of instability causes the loss of optical activity after a finite number of absorptive transitions and thus causes changes in the resulting color of the LED, limiting the lifetime of the LED. In this regard, high quantum yield small organic molecules or fluorescent polymers are useful for creating pure white emissions using UV/blue LEDs [1,2,6].

Small organic molecule tris-(8-hydroxyquinoline) aluminum (Alq3) and polymer poly3 butyltheophene (P3BT) are environmentally friendly fluorescent materials with broad luminescence in the green and red portions of the visible spectrum and excellent transport properties. These materials have been used in optoelectronic devices, such as organic light-emitting diodes (OLEDs) and organic field-effect transistors (OFETs) [9–15]. However, their composite materials have not yet been used to engineer broad luminescence at a sub-micrometer scale. Electrospinning is a simple and convenient process to prepare continuous sub-micrometer diameter fibers by spraying the solution of desired compounds through a strong electric field [12,13]. This process has the significant advantages of being able to encapsulate color tunable multicolor organic molecules in transparent polymers and effectively coating any substrate. In this work, we prepared Alq3/P3BT composite electrospun microfibers, which emit white PL, covering the green and red colors in the visible spectrum by coupling with a blue LED.

2. Experimental

We prepared the Alq3/P3BT composite microfiber using the electrospinning process. The solution was prepared in chloroform with Alq3, P3BT, and polyethylene oxide (PEO) powder purchased from Sigma–Aldrich. PEO was used to provide the viscosity required for the electrospinning process [10–13]. We maintained a 2:1 weight ratio of the Alq3/PEO weights in the electrospinning

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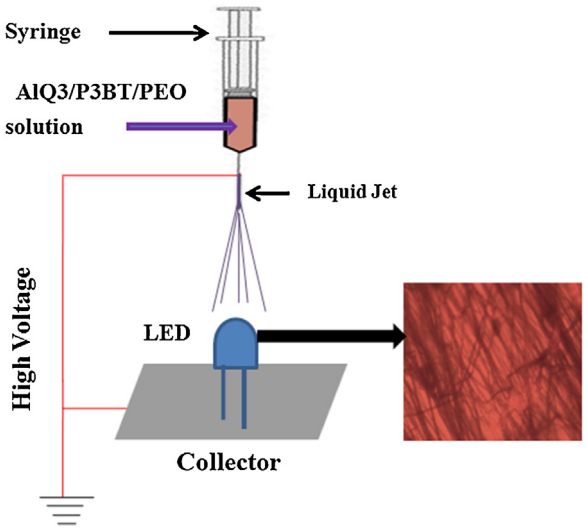

Fig. 1. Schematic of the preparation and collection of the electrospun fibers using an electrospinning process in a solution of Alq3, P3BT and PEO in chloroform. The optical image represents the electrospun fibers collected on an arbitrary region of the LED surface.

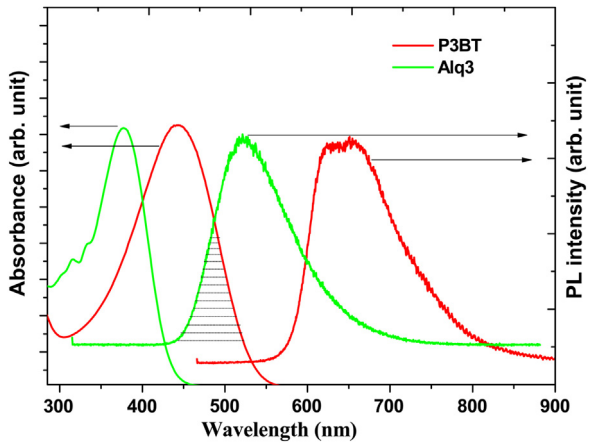

Fig. 2. Normalized absorption spectra obtained from the electrospun fiber solution in ethyl alcohol, and single-strand confocal PL spectra of the Alq3 (green) and P3BT (red). The dashed region represents the overlap of the absorption spectrum of the P3BT electrospun fibers with the emission spectra of the Alq3 electrospun fibers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

solution, while different weight ratios of Alq3 to P3BT were used in the electrospinning solutions to tune the green and red colors in the resultant microfiber. The solutions were stirred in a magnetic stirrer for 6 h at 65 °C and then electrospun from a 12 mL syringe with a 0.4 mm diameter needle using the manufactured electrospinning equipment (Nano NC) operating at a high DC voltage. Electrospinning was performed at a potential of 15 kV, and the distance between the electrodes was maintained at 17 cm. The rate of spinning was held at 100 μL per minute using a motorized syringe pump. As shown in the schematic diagram in Fig. 1, we used different Alq3 to P3BT weight ratios in the solution to optimize the white emissions of the electrospun fibers. To demonstrate that, we directly collected the electrospun fibers on the surface of the blue LED. The representative optical image of the white light-emitting electrospun fibers collected on the surface of the LED is shown in Fig. 1. All of the experiments were carried out at ambient temperature.

Confocal photoluminescence (PL) spectroscopy was performed with a 405 nm diode laser in a lab-built laser confocal microscope (LCM). The typical laser power on the sample was 7 μW. The microscope objective (100×, *NA* = 1.4) was used in back-scattering geometry. We also performed confocal Raman spectroscopy using the same microscope system with a 632.5 nm He–Ne gas laser. We used a commercial LED (Thorlabs) that emits light with a 405 nm wavelength.

3. Results and discussion

3.1. Optical absorption and confocal PL spectroscopy analysis

Fig. 2(a) represents the normalized absorption spectra obtained from the solution in ethyl alcohol and the single strand confocal PL spectra of the Alq3 (green) and P3BT (red) electrospun fibers. The Alq3 and P3BT electrospun fibers showed broad absorption spectra with the main peaks at approximately 375 nm and 440 nm, respectively, which are similar to previously reported results [10,11,16]. We note that Alq3 and P3BT have common absorption in the visible region at 405 nm, at which both Alq3 and P3BT can be photo-excited. Also, the absorption spectrum of the P3BT overlaps with the emission spectra of the Alq3 electrospun fibers, suggesting the high possibility of FRET from Alq3 to P3BT in the Alq3/P3BT composite materials [17]. Broad PL spectra covering the full green and red portions of the visible spectrum are observed at the single strand level of the Alq3 and P3BT electrospun fibers, as shown in Fig. 2, similar to previously reported results [10,11,16].

3.2. Confocal PL mapping and Raman spectroscopy analysis

We performed PL spectral mapping of the Alq3/P3BT composite electrospun fibers prepared from the solution containing a 1:1 Alq3:P3BT weight ratio and analyzed the distribution of the Alq3 and P3BT molecules at the single strand level. As shown in Fig. 3(a), the PL mapping image of the Alq3/P3BT composite electrospun fibers obtained by integrating the spectra in the wavelength range from 450 nm to 800 nm demonstrates the variation of the luminescence along the microfiber. The intensity variation in the PL arises from the inhomogeneous distribution of the Alq3 and P3BT along the microfiber during the microfiber formation process. Fig. 3(b) demonstrates the actual distribution of the P3BT and Alq3 molecules along the electrospun fibers. The variation in the molecular distribution is calculated by the ratio of the P3BT PL intensity to the Alq3 PL intensity (I_P/I_A) in the composite electrospun fibers in each pixel of the PL mapping image. The higher intensity ratio along the electrospun fibers represents the P3BT-rich region. The observed inhomogeneity of Alq3 and P3BT along the electrospun fibers may be due to the slightly different electrospinning efficiencies of the small molecule (Alq3) and polymer (P3BT) originating from their intrinsic solution property in the same solvent (chloroform) at room temperature [10,12,13]. We also calculate the average PL spectra (Fig. 3(c)) of the electrospun fibers shown in Fig. 3(a), where the higher PL band intensity originating from the P3BT is more clearly observed compared to that of Alq3. This higher PL intensity from the P3BT molecules in the composite electrospun fibers is believed to be due to FRET between the Alq3, which acts as the donor, and P3BT, which acts as the acceptor.

Fig. 3(d) displays the representative Raman spectrum obtained using a 632.8 nm laser line from a single strand of the composite Alq3/P3BT electrospun fiber, which confirms the formation of the Alq3/P3BT composite electrospun fibers. The Raman spectrum consists of the major Raman bands of Alq3, marked with green arrows at 1400 cm^{-1} and 1598 cm^{-1} in Fig. 3(d) and assigned as the CH bend and ring stretching modes, respectively [16,18]. The Raman bands of the P3BT are marked with red arrows at 1378 cm^{-1} and 1441 cm^{-1} and are assigned as the stretching mode of the C_α—C_β