High performance light emitting transistors
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Citation: Applied Physics Letters 92, 183304 (2008); doi: 10.1063/1.2920436
View online: http://dx.doi.org/10.1063/1.2920436
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High performance light emitting transistors

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(Received 4 March 2008; accepted 10 April 2008; published online 9 May 2008)

Solution processed light emitting field-effect transistors (LEFETs) with peak brightness exceeding 2500 cd/m² and external quantum efficiency of 0.15% are demonstrated. The devices utilized a bilayer film comprising a hole transporting polymer, poly(2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-b]thiophene) and a light emitting polymer, Super Yellow, a polyphenylenevinylene derivative. The LEFETs were fabricated in the bottom gate architecture with top-contact Ca/Ag as source/drain electrodes. Light emission was controlled by the gate voltage which controls the hole current. These results indicate that high brightness LEFETs can be made by using the bilayer film (hole transporting layer and a light emitting polymer). © 2008 American Institute of Physics.

[DOI: 10.1063/1.2920436]

Organic light emitting field-effect transistors (LEFETs) are attracting interest due to a number of applications such as simplified pixels in flat panel displays, optoelectronic devices in communications, and potentially electronic devices as the anode for the OLED with electron injection by tunneling from the drain electrode. 1,8

The brightness and light emission performance reported for LEFETs in the literature are, however, rather low. This is mainly due to the fact that the organic materials used to date in LEFETs possess either a low carrier mobility with high photoluminescence (PL), such as the amorphous organic semiconductors used in OLEDs (Refs. 4–8) or high mobility with weak PL such as in single crystal materials. 1,9,10 To obtain high performance, materials must (i) be capable of ambipolar carrier (hole/electron) injection and transport from their respective source-drain electrodes (e.g., Ca, Ag), (ii) have high PL efficiency in a thin film, and (iii) have relatively good carrier transport. Balancing these three factors in a single layer LETFT device structure is a challenging task. Two component layered films consisting of a charge transport layer and a light emitting layer could be an alternative approach to achieve this goal. This approach is possible for the evaporated organic films, 11–14 but challenging for the spin cast films.

In this paper, we demonstrate a simple method to improve the light emission by fabricating a bilayer film using solution processing. The LEFETs comprised a hole transporting polymer, poly(2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-b]thiophene) (PBT TT-C14) between the gate dielectric and the luminescent polymer layer. For the latter, we used “Super Yellow” (SY) a polyphenylenevinylene derivative as the light emitting polymer. The devices were fabricated in the bottom gate configuration with 400 nm thick silicon nitride as the gate dielectric and Ag/Ca as source/drain electrodes. Excellent output and transfer characteristics were demonstrated with brightness exceeding 2500 cd/m² and with external quantum efficiency (EQE) 0.15%. The light emission was controlled by the gate voltage which, in turn, controlled the hole current.

Figure 1 shows a diagram of the device architecture and the molecular structures of the materials used. A heavily doped n-type silicon wafer functioned as the substrate and as the gate electrode. The n++ Si gate electrode was first coated with 400 nm of silicon nitride deposited by plasma-enhanced chemical-vapor deposition. The PBT TT-C14 (0.3% in chlorobenzene) was then spin cast onto the substrate at 3000 rpm to serve as a hole transporting layer. The samples were annealed at 150 °C for 10 min in a glovebox. The soluble PPV derivative, SY, was spin cast from solution at 2000 rpm to form the electroluminescent semiconducting polymer layer. After film deposition, the multilayer samples were annealed at 200 °C for 30 min in a glovebox. The samples were then

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FIG. 1. (Color online) (a) Molecular structures of PBT TT-C14 (R=C14H29) and (b) SY. The lower panel is a schematic diagram of the device architecture.
mounted onto a silicon shadow mask to complete the device fabrication using an angled evaporation of Ca first followed by Ag deposition. This fabrication process is described in our earlier publication in detail.\(^3\) The channel length between source and drain electrodes was 19 μm and the channel width was 1000 μm. PBTT-T-C14 was selected as the hole transport layer because (i) it is known to have a high hole mobility, (ii) it is solution processed but only weakly soluble in the solvent used for the SY, and (iii) it does not quench the PL of the SY.

The devices were tested using a Signatone probe station that was housed in a nitrogen glovebox. All electrical and optical measurements were carried out in nitrogen atmosphere at <1.0 ppm oxygen. A Keithley 4200 system was used to gather the electrical data, while the light emission was simultaneously collected with a Hamamatsu photomultiplier (PMT). The brightness was calculated by comparing the photocurrent in a PMT with a device of known brightness (79 cd/m\(^2\)) and light emission area (500×500 μm\(^2\)). A Super Yellow light emitting electrochemical cell (LEC) was fabricated and used for this comparison.\(^5\) The photocurrent in the PMT was corrected for the effective light emitting area to get the correct brightness value. The brightness and current/voltage measurements of a reference LEC was measured in a glovebox using a Keithley 2400/2000 current/voltage source unit calibrated with a silicon photodiode. The EQE was calculated from the brightness, the drain current, and the emission spectrum of the device.\(^6\)

Figures 2(a) and 2(b) show the device output and transfer characteristics. The gate electrode was biased negative with respect to ground (Ca electrode grounded). These results indicate hole-dominated transport with distinct linear and saturation regimes for \(I_{DS}\) at low \(V_{DS}\) (0 to −30 V) and high \(V_{DS}\) (−30 to −100 V), respectively. The drain current reached a maximum value of 100 μA with an on/off current ratio 10\(^5\). The field-effect mobility was extracted in the saturation regime from transfer characteristics,

\[
I_{DS} = \frac{1}{2} \mu C \frac{W}{L} (V_{GS} - V_T)^2,
\]

where \(\mu\) is the field-effect mobility, \(C\) is the capacitance per unit area of the gate dielectric (17 nF/cm\(^2\)), and \(V_T\) is the threshold. From the data in the saturation regime, we find \(\mu = 3 \times 10^{-2} \text{ cm}^2/\text{V s}\). This hole mobility is higher by a factor of \(\sim 10^2\) than that obtained for the SY ambipolar LEFET fabricated without the PBT-TT-C14 hole transporting layer.\(^4\)

These results indicate that the hole transport occurs, through the PBT-TT-C14, near the dielectric interface.

Figure 3 shows an optical image (inset) and the electroluminescence (EL) and PL spectra from the same devices. The EL spectrum is somewhat narrower than the PL spectrum, but independent of the biasing voltages. With the transistor biased “on,” bright yellow-green light was visible to the eye. The light emission zone was close to the edge of the Ca electrode. The width of the emission zone was 4.0 ± 0.5 μm. The location of the emission zone was independent of the gate bias. The EL and PL spectra are almost identical, indicating that the EL originates from singlet excitons.

Figures 2(a) and 2(b) also show both the brightness, cd/m\(^2\) versus \(V_{DS}\) at various gate voltages and the optical transfer characteristic (brightness versus \(V_{GS}\) at \(V_{DS}=-100\) V) for the gate electrode biased negative with respect to ground. The data indicate excellent optical modulation by the gate voltage. The brightness increases with \(V_{DS}\) and \(V_{GS}\) and then reaches saturation. The brightness is directly proportional to \(I_{DS}\). The light turn-on (defined as the gate voltage required to achieve brightness of \(\sim 0.1\) cd/m\(^2\)) was at \(V_{GS} \approx -20\) V for \(V_{DS}=-100\) V. The maximum brightness approximately reached 1500 cd/m\(^2\) at \(V_{GS} = -100\) V. The inset of Fig. 3(b) show the EQE as a function of gate voltage at \(V_{DS}=-100\) V. The maximum EQE was \(\sim 0.075\%\) at 1500 cd/m\(^2\) (and \(V_{GS} = V_{DS} = -100\) V).
From the channel dimensions and film thickness (1000 μm channel width and 100 nm PBTTT-C14 layer thickness), the maximum hole current density at 200 V is estimated to be approximately 50 A/cm². The current density in the accumulation region (estimated assuming carrier confinement to within a thickness of ~2 nm near the gate-dielectric/semiconductor interface) is therefore ~2.5 kA/cm². This current density is higher than the current density obtained for a conventional OLED structure (~10⁻² A/cm²) and comparable to single crystal LEFETs Ref. 17 (~4 kA/cm²). These results suggest that by further tuning the electron and hole mobilities, changing the channel dimensions, and pulsing to higher voltages, sufficiently high brightness to enable organic injection lasing might well be feasible. The density induced for carriers can be further enhanced by selection of a high k dielectric with low leakage current.

In summary, we have demonstrated high brightness light emission in a transistor configuration using solution processed semiconducting polymer bilayer films. The LEFET exhibited excellent electrical characteristics. Light emission was visible with brightness exceeding 2500 cd/m² at EQE of 0.15%. The brightness is controlled by the gate voltage.

Support for LEFET and gate controlled LED research was provided by the Air Force Office of Scientific Research (Charles Lee, Program Officer) and by the National Science Foundation (Polymer program, NSF-DMR-0602280). We thank Dr. Martin Heeney (Queen Mary, University of London) and Professor Iain McCulloch (Imperial College London) for supplying the BPTTT-C14 material for our use (the PBTTT-C14 was synthesized at Merck). The SY material was provided by Covion.


![Image](image_url)