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Characterization of the Anomalous Temperature-dependent Carrier Transports in the Disordered ITO/PEDOT/PF/Ca/Al Polymer Light-emitting Diodes

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1. Introduction

Organic electronics have received widespread attention in the past decade due to intensive applications of organic light-emitting diodes (OLEDs). Due to low cost manufacturing and mechanical flexibility makes these materials promising, many display applications in lightening, flat panel displays, and optically pumped organic thin films in stimulated emission [1]. However, several research groups have attempted to describe the current–voltage (I–V) in OLEDs have been examined on the basis of trap charge limited current (TCLC) and space charge limited current (SCLC) theory under various conditions such as the existence of trap states or field dependent mobility. Further, the Berthelot-type microscopic model has successfully described the linear and the nonlinear temperature dependent behaviors of many disordered systems [2]. It has recently shown that the I–V and EL characteristics of a vacuum-deposited polymer light-emitting diodes (PLEDs) [3] is consistent with the injection of charge into a thin film with a large density of traps distributed in energy beneath the lowest unoccupied molecular orbital (LUMO). In this article, we studied the anomalous temperature-dependent electrical characteristics of the PF-based PLEDs at a temperature range of 200 to 300 K by examinations of the I–V characteristics temperature evolution. The experimental results also revealed that the carrier-transport process is essentially attributed to an exponential distribution of traps characterized by two parameters namely the density of traps H_t, and the characteristic energy of the distribution E_t.

2. Experiment

Organic layers were deposited by spin coater onto a glass substrate coated with a patterned indium-tin-oxide (ITO) electrode. A hole injection layer PEDOT:PSS was spin coated onto ITO glass substrate. The active luminescent polymer film PF was spin coated onto PEDOT:PSS layer. Thereafter, the samples were transferred into thermal evaporation chamber that the electron injection layer, Ca (30 nm) and Al cathode (~100 nm) were evaporated sequentially. For the temperature dependent I–V measurements, the samples were mounted in a closed-cycle He cryostat and carried out using a semiconductor parameter analyzer (HP 4156) in the temperature range of 200 to 300 K.

3. Results and discussion

To elucidate the carrier transport of the PF-based PLEDs, we performed I-V measurements over the temperature range of 200 to 300 K. Fig. 1 illustrates the temperature-dependent conductance, i.e., ln(dI/dV) vs. T, for PLED with different voltages, respectively. Based on the Berthelot-type model, the electrical conductance of the sample can be described by [2]

$$\frac{dI}{dV} = C_0 \exp\left(\frac{T}{T_B}\right) \tag{1}$$

where C_0 is a temperature-independent constant and the so-called Berthelot temperature T_B is a carrier hopping related temperature corresponding to the slope of each straight line in the Fig. 1.

By using the definition of Berthelot-type model, T_B is the Berthelot temperature given by the expression $T_B=\hbar^2/(2\pi^2S^2m_e^*k)$. As seen from the plots, the sample with high driving voltage exhibits a higher T_B, indicating that carrier transports in a disordered system manifest Berthelot-type behaviors. This expression represents that a shorter static barrier width S would result in a higher Berthelot-temperature. As strong electron-electron scattering arising from a high excitation and a microcrystalline randomization, a shorter static barrier width led to that the Berthelot-type process correspondingly dominated with a large T_B. Therefore, it has been that T_B increase gradually with increasing driving voltage.

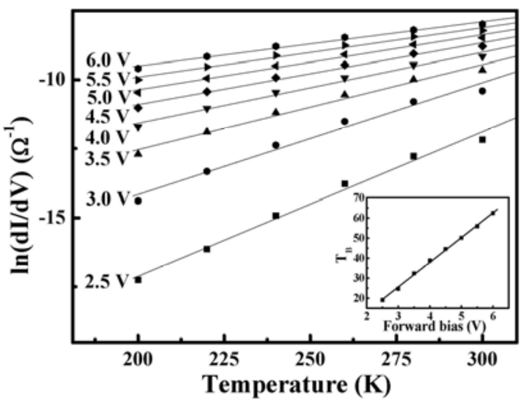

Fig. 1 The temperature-dependent conductance, i.e., ln(dI/dV), in the temperature range of 200-300 K. The straight line shows the slope with Berthelot temperature T_B for PLED with different voltages, respectively. The inset shows the T_B as function of forward bias voltages for PLED device.

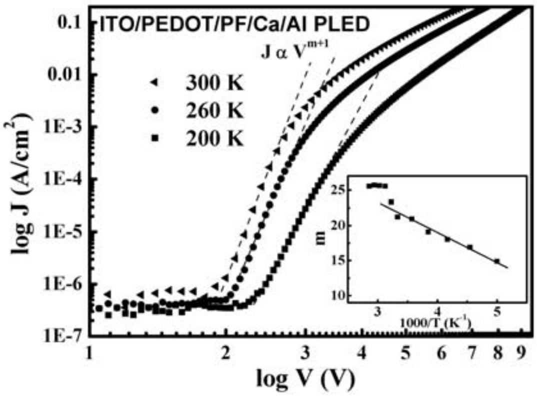

Fig. 2 Current-voltage curves of PLED device at 200 K, 260 K and 300 K, respectively. The dashed lines show the slope with TCLC power-law factor *m* = 16.1, 20.3, and 20.7 for PLED at 200 K, 260 K and 300 K, respectively. The inset shows the power-law factor as a function of reciprocal temperature for PLED device.

Figure 2 shows the J-V characteristics of the PLEDs as a function of the ambient temperature. The ideal J-V curve of the PLEDs can distinguish three different parts of the carrier transmit mechanism, while beginning to increase the bias voltage. It is quite clear that the current density J varies with respect to V^{m+1}, where m+1 is defined as slope, in a specific injection regime. Under low bias situation, current-voltage characteristic logJ-logV curve is ohmic conduction with slope 1. While increases the bias, the mechanism of logJ-logV curve transforms the trap charge limited current (TCLC), the value of slope when this situation is larger which means the power law which slope>8. Continue applied bias, The current flow in trap free conducting organic materials with field independent mobility μ is described by the Mott and Gurney model of space charge limited current (SCLC). Now, the relationship between the voltage and current is regarding to the trap-charge limited conduction (TCLC) as expressed [1]:

$$J = \mu N_v q^{1-m} \left(\frac{2m+1}{m+1}\right)^{m+1} \left(\frac{\varepsilon_s \varepsilon_0}{H_t}\frac{m}{m+1}\right)^m \frac{V^{m+1}}{d^{2m+1}} \qquad (2)$$

where H_t is the density of traps, E_t is the characteristic constant of the distribution also often expressed as a characteristic temperature T_c ($E_t = kT_c$), k is the Boltzman constant, ε_0 is the permittivity of free space, and ε_s is the dielectric constant of the material, μ is the carrier mobility, N_v is the density of states in the relevant band, $m=T_c/T$, T is the measurement temperature, and d is the sample thickness.

As shown in Fig. 2, the dashed lines show the slope with TCLC power-law factor *m* = 16.1, 20.3, and 20.7 for PLED at 200 K, 260 K and 300 K, respectively. The inset shows the power-law factor as a function of reciprocal temperature for PLED device. The power-law factors increased as the temperature increased, it has corroborated that the Berthelot-type behavior were response to the microstructure disordering arising from the organic nonstoichiometry.

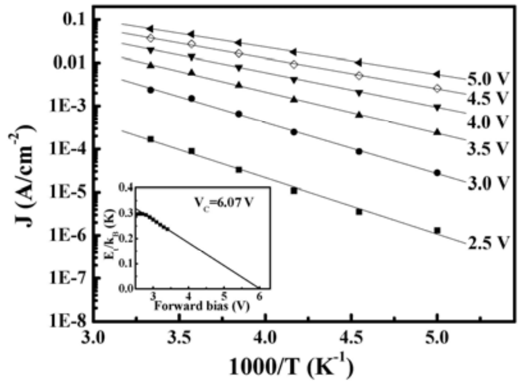

Fig. 3 The logJ as a function of reciprocal temperature for the PLED device with different voltages. The inset shows a plot of E_a versus *V*, with V_c as the intercept.

Furthermore, we use the following equation to calculate the trap density of polyfluorene (PF):

$$J = \left(\frac{\mu N_v qV}{d}\right) f(m) \exp\left[-\frac{E_t}{kT}\ln\left(\frac{qH_t d^2}{2\varepsilon_s\varepsilon_0 V}\right)\right] \qquad (3)$$

and

$$f(m) = \left(\frac{2m+1}{m+1}\right)^{m+1}\left(\frac{m}{m+1}\right)^m \frac{m}{2^m}$$

when the variable m in f(m) is larger than 2, f(m) is closing to 0.5,and Eq. (3) simplify to Eq. (4):

$$J = \left(\frac{\mu N_v qV}{2d}\right) \exp\left[-\frac{E_t}{kT}\ln\left(\frac{qH_t d^2}{2\varepsilon_s\varepsilon_0 V}\right)\right] \qquad (4)$$

and assumed

$$E_a = \frac{E_t}{k}\ln\left(\frac{qH_t d^2}{2\varepsilon_s\varepsilon_0 V}\right)$$

where $\mu=1\times10^{-6}$ cm^2/V, $N_v=1\times10^{20}$ cm^{-3}, d=250 nm, $\varepsilon_s=2.5$, $\varepsilon_0=8.85\times10^{-12}$ F/m. Fig. 3 shows the logJ as a function of reciprocal temperature for the PLED device with different voltages. It has examined the value of E_a by use Eq. (4) over the temperatures 200 K to 300 K with different voltage. It has been found that value of E_a decreased with increased bias voltage. The insert figure shows a plot of E_t/k versus bias voltage, with V_c as the intercept is 6.07 V. If E_a=0, we can calculate the density of trap $H_t=2.69\times10^{16}$ cm^{-3} by $H_t=2\varepsilon_s\varepsilon_0 V_C/qd^2$ with some simple parameters of V_c.

4. Conclusions

In this study, we show the experimental results revealed that the carrier-transport process is essentially attributed to an exponential distribution of traps characterized by two parameters namely the density of traps H_t, and the characteristic energy of the distribution E_t. We also verify the organic semiconductor devices of disorder materials can use semiconductor theory to elucidate the electrical characteristic.

References

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