Dependence of the dynamics of exciton transport, energy relaxation, and localization on dopant concentration in disordered C545T-doped Alq3 organic semiconductors

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Abstract: The dynamics of exciton transport, energy relaxation, and localization in disordered Tris(8-quinolinolato)-aluminum (Alq3) organic semiconductors with different 10-(2-benzothiazolyl)-1, 1, 7, 7-tetramethyl-2, 3, 6, 7-tetrahydro-1H, 5H, 11H-benzo[i]pyran[6, 7, 8-i]quinoliniz-11-one (C545T) dopant concentrations were reported. The increasing trend of the Stokes Shift (737–764 meV) with increasing dopant concentrations is consistent with the degree of disorder and a more effective Förster energy transfer from Alq3 to C545T. In addition, a dynamic scenario representing possible paths of the exciton transport (hopping) among host molecules and the competition of the exciton transport from host molecules into the deep site traps (localized states) and aggregations was proposed to elucidate the recombination dynamics in disordered C545T-doped Alq3 organic semiconductors. The early-stage decay times, decreasing with increasing emission photon energy, show the characteristic of the exciton hopping and energy relaxation processes within the inhomogeneously broadened density-of-states in organic semiconductors. Because the current-voltage (J-V) characteristics of the C545T-doped organic light emitting diode (OLED) fitted well with the power law J-V^m (m>2), the carrier transport behaviours can be described by the trapped-control mode and the tail state distribution can be approximated by the exponential trap distribution. With the approximation of an exponential distribution for the tail states, the characteristic energy (E_n0), radiative recombination lifetime (τ_rad), and localization depth (E_0) associated with the dynamics of exciton energy relaxation and localization can be quantitatively determined. The much larger E_0 (40–120 meV), increasing with the dopant concentration, than other disordered semiconductors (2–34 meV) indicates a strong localization effect in such doped organic semiconductors. Also, the strong dependence of E_n0 on the dopant concentration shows that a relatively small dopant concentration can enhance the degree of disorder and greatly affect the recombination dynamics. Furthermore, the observed optical properties and dynamic scenario of C545T-doped Alq3 films are found to be consistent with the carrier transport and recombination dynamics of C545T-doped Alq3 OLEDs.

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References and links

1. Introduction

Organic semiconductors are presently a field of intensive research due to their application in organic field-effect transistors, organic light-emitting diodes (OLEDs) [1], flexible displays [2], and flexible solar cells [3]. Organic semiconductors offer the possibility of tailoring the chemical structure to adapt the material functionally and improve device performance. The photoluminescence (PL) in organic materials is due to the radiative recombination of photogenerated excitons, while the electroluminescence in the multilayer OLEDs comes from the dynamic behavior of charge carrier injection, transport, and recombination. Currently, carrier transport (carrier hopping) and energy relaxation in doped OLEDs are acute topics of excitonic physics [4–7]. In organic systems, the disorder leads to a localization of the electronic wave function and a broad density-of-states (DOS). The disordered model suggests that the carrier transporting states are energy localized [8–10]. In such a disordered system, carrier transport (jump) rate among localized states are governed by both positional and energetic disorders [11,12]. The two types of disorders are correlated because the positional disorder will induce energy disorder via the potential energy of the interaction, which depends on the relative position of neighboring molecules. In addition, the distribution of the DOS for the transport states can be described as a Gaussian function. The width $\sigma \sim 500$ meV of the DOS represents the disorder of the transport states. Numerical investigations of hopping transport were undertaken by using the Monte Carlo simulations [9,10] and Gaussian disorder model [13,14]. Because temperature and electric field can redistribute the DOS of the transporting states, the transport process can be activated and modified by temperature and electric field [15]. For an energetically random system, the energy disorder affects the carrier transport characteristics. Energetically upward jumps require thermal activation and take a longer time than downward jumps. Hence, a localized state can promptly capture a carrier and keep it localized for a long time [8].

Device applications of disordered OLEDs often require doping of these materials to achieve a higher density of free carriers [4–7], efficient color tuning, good device efficiency, and narrow emission spectrum width [1–3]. Doping of an energetically disordered hopping system not only produces free charge carriers, but also creates localized (relatively deep) states in addition to the intrinsic DOS distribution [4–7]. An analytic model of carrier hopping in weakly- and heavily-doped disordered organic materials was proposed [4–7]. At low doping levels, the Coulomb DOS broadening dominates and the mobility decreases with increasing doping levels. At higher doping levels, the Coulomb DOS broadening becomes almost saturated and the filling of deep traps leads to a shallower energy distribution of localized states. The mobility steeply increases with the increasing of doping levels. In previous study, the carrier transport and recombination dynamics of OLEDs were found to be strongly depend on dopant concentration [1]. In the lightly-doped sample, a higher carrier mobility and better device performance were observed compared to the undoped and highly-doped samples. Due to the aggregations in the highly-doped sample, carrier quenching, as well as nonradiative recombination, degraded the device performance. The trends of the radiative and nonradiative decay rates suggest that the lightly-doped sample can exhibit better luminescence efficiency at higher applied voltage, while the highly-doped sample shows poorer luminescence efficiency, even operated at lower applied voltage.

In OLEDs, the current-voltage ($J$-$V$) characteristics were often used to examine the carrier transport behaviours [16–20]. The space-charge-limited current (SCLC), $J$, often shows the power law $J \sim V^m$ dependence on voltage $V$. For a trap-free material, the SCLC, $J$, follows the well-known Child’s law with $V^2$ dependence [16]. In disordered materials, traps become important for determining the carrier transport behaviour, and the SCLC, $J$, often exhibits the power law $J \sim V^m (m>2)$ characteristic [17–20]. With the assumption of the exponential distribution of the trap states in the deep tail of the DOS, the trap-controlled model can
explain well the $J$-$V$ characteristic [17–20]. In addition, time-resolved photoluminescence (TRPL) measurement is also a powerful tool to study excitation dynamics and energy relaxation in disordered organic semiconductors [13,14]. The transient luminescence at different detection energies can reveal the dynamics corresponding to different energetic positions within the DOS. In conjugated polymers, such as poly(p-phenylenevinylene) (PPV), a spectral red-shift of about 30 meV within the first 50 picoseconds (ps) is observed [13]. The energy relaxation in the broadened DOS of the polymer was proposed to elucidate the dynamic population and depopulation at different energies. Since the sub-ps PL decay time and the low quantum efficiency indicate that the majority of carriers decay nonradiatively, the proposed PL dynamics of low efficiency PPV can’t present the whole scenario. Although the recombination dynamics of OLEDs have been reported, the detailed characteristics and parameters associated with the dynamics of exciton transport, energy relaxation, and localization in disordered organic semiconductors with different dopant concentrations have not been quantitatively determined yet.

In this study, to understand the dynamics of exciton transport, energy relaxation, and localization in doped organic semiconductors, four Tris(8-quinolinolato)-aluminum (Alq$_3$) samples with different 10-(2-benzothiazolyl)-1, 1, 7, 7-tetramethyl-2, 3, 6, 7-tetrahydro-1H, 5H, 11H-benzo[6, 7, 8-i] quinolizin-11-one (C545T) dopant concentrations were prepared. The increasing trend of the Stokes Shift (SS) (737~764 meV) with increasing dopant concentrations is consistent with the degree of disorder and a more effective Förster energy transfer from Alq$_3$ to C545T. In addition, a dynamic scenario representing possible paths of the exciton transport among host molecules and the competition of the exciton transport from host molecules into the deep site traps (localized states) and aggregations was proposed to elucidate the recombination dynamics in disordered C545T-doped Alq$_3$ organic semiconductors. With the approximation of an exponential distribution for the tail states, the characteristic energy ($E_m$), radiative recombination lifetime ($\tau_{rad}$), and localization depth ($E_0$) associated with the dynamics of exciton energy relaxation and localization can be quantitatively determined.

This paper is organized as follows: In section 2, sample structures and experimental procedures are described. In section 3, experimental results and discussions of the dynamics of exciton transport, energy relaxation, and localization in disordered C545T-doped Alq$_3$ organic semiconductors are reported. Finally, conclusions are drawn in section 4.

2. Sample structures and experimental procedures

As shown in Fig. 1(a), the samples were fabricated by vacuum deposition of the organic materials onto an indium-tin-oxide(ITO)-coated glass at a deposition rate of 1-2 Å/sec at 10$^{-6}$ Torr. The dopant concentrations of C545T in Alq$_3$ were 1%, 3%, 5%, and 7%, respectively, for four samples. Figures 1(b) and 1(c) show the molecular structures of Alq$_3$ and C545T, respectively.

The morphological study was done by a scanning electron microscopy (SEM) (Hitachi, Model S-4300N) with the excitation 5kV electrons. The PL and PLE (photoluminescence
excitation) spectra are measured by a fluorescence spectrophotometer (Hitachi, Model 4500). For TRPL measurements, a picosecond diode laser (PicoQuant, Model PDL 800B) generated optical pulses of 100 ps width with a 20 MHz repetition rate to excite the samples. The excitation photon energy and average power were 3.324 eV (373 nm) and 10 mW, respectively. Light emitted from the sample was detected by a photomultiplier (PMT) and a monochromator. The signal from the PMT was recorded by means of time-correlated single photon counting technology (PicoQuant, Model TimeHarp 200). The overall time resolution of the system was 50 ps. The samples were placed in a cryostat for low-temperature measurements.

3. Results and discussions

3.1 SEM results

The morphology of the 1% C545T-doped Alq3 sample shows a homogeneous and featureless image while that of the 3% C545T-doped Alq3 sample shows aggregations [1]. Due to guest-host interactions, energy states of neighboring molecules may be raised or lowered as compared to the pristine host molecules. Also, because guest molecules (C545T) are chemically different from host molecules (Alq3), guest molecules tend to form aggregations. Aggregations were also observed in DCM-doped Alq3 films [21]. The random distribution of aggregations represents additional spatially-distributed potential minimums, which could easily trap carriers for self-quenching and luminescence losses. The varied potential further increases the energy disorder and influences the recombination dynamics. In the following discussions, photogenerated carriers were considered as strongly bound excitons (Frenkel excitons) rather than free charge carriers.

3.2 PL and PLE results

Figure 2 shows the PL and PLE spectra of the 1%, 3%, 5%, and 7% C545T-doped Alq3 films at room temperature (RT). The PL spectrum of Alq3 with peak energy near 2.407 eV is shown as a reference. In each sample, the PLE spectrum shows an Alq3 absorption feature (~3.155 eV) besides the C545T absorption peak near 2.53 eV.

In the lightly-doped samples, the high energy side of the PL spectra disappeared and the PL spectra showed narrow widths and lower peak energy positions. The narrow spectral widths in the doped samples suggest that dopants in OLEDs can dramatically change the luminescence properties and are beneficial for color purity. Because the high energy side of the Alq3 PL spectrum overlaps with the absorption spectrum of the C545T, Förster energy transfer from Alq3 to C545T occurs. The energy level diagram of Alq3 and C545T and the energy transfer process between molecules are shown in the inset of Fig. 2(a). Hence, narrow spectral widths and lower peak energy positions were observed in the PL spectra. In addition, as the dopant concentration increases, the peak position was slightly red-shifted and a shoulder in the low-energy side becomes apparent. Similar phenomena, attributed to aggregations, were also observed in the Alq3 OLEDs with C545T dopants in our previous study [1]. The larger overlap between the PL spectra of Alq3 and apparent absorption of C545T indicates an efficient Förster energy transfer from Alq3 to C545T in the highly-doped sample. Also, because the S1 level of the dopant is lower than that of Alq3, the dopant can trap carriers for luminescence. This leads to a lower average potential energy. Hence, the red-shifted PL peak positions and a prominent low-energy side in the PL spectra were observed in highly-doped samples.
Fig. 2. Normalized PL (the solid lines, left ordinate) and PLE (the dash lines, right ordinate) spectra of 1%, 3%, 5%, and 7% C545T-doped Alq₃ samples. The dotted line shows the PL spectrum of Alq₃ as a reference. The inset in (a) shows an energy level diagram of the Alq₃:C545T system with the Förster energy transfer process. SS is the Stokes Shift.

In each sample, a large SS of PL peak with respect to Alq₃ absorption peak was observed. This typical observation provides evidence for the occurrence of energy relaxation processes in disordered organic semiconductors. Site-selective luminescence spectroscopy has revealed that the different widths of emission and absorption bands were due to a strong inhomogeneous broadening of the optical transition [22,23]. After excitation into higher energy states, relaxation processes downward populate the lower energy states. The radiative transition to the ground state occurs from the lower energy states of the DOS. Hence, the spectral width of the emission band is narrower than that of the absorption band. In addition, the magnitudes of the SS’s of the samples of 1%, 3%, 5%, and 7% C545T-doped Alq₃ were about 737, 756, 759, and 764 meV, respectively. Because the S₁ level of the dopant is lower than that of Alq₃, the increasing trend of the SS with increasing dopant concentration is consistent with a more efficient Förster energy transfer from Alq₃ to C545T. Also, the aggregations in the highly-doped sample not only represent additional spatially distributed potential minimums, but also broaden the effective DOS distribution. Hence, the aggregations enhance the degree of disorder and the larger SS is consistent with the larger PL spectral width.

3.3 Dynamics of exciton transport, energy relaxation, and localization

To understand the detailed characteristics and parameters associated with the dynamics of exciton transport, energy relaxation, and localization, TRPL measurements were conducted. The low-temperature (10K) transient luminescence intensities at several emission photon energies of the 1% C545T-doped Alq₃ sample are shown in Fig. 3(a). The detection energy corresponds to different energy positions within the DOS.

The curve corresponding to the high-energy side (the curve of 2.58eV) shows non-exponential (or stretched exponential) fluorescence decays, which are relatively faster in the early stages and slower in the extended ranges of the later stages. The non-exponential (or stretched exponential) decay can be explained by energy relaxation and/or quenching of
excitons via Förster energy transfer either among host molecules within intrinsic DOS or from an excited host molecule to a guest exciton acceptor [24]. It also suggests that hopping of excitons to quenching centers can be described as exciton hopping between host molecules, and the exciton acceptors can be incorporated as deep traps distributed at the tail of the intrinsic DOS [24]. In addition, near the PL spectral peak and the low-energy side, there exist delayed slow rises for a few hundred ps in the early stages, as highlighted with the ellipses in the curves of 2.21, 2.29, and 2.38 eV. Similar temporal behaviors, which were attributed to energy relaxation and the hopping process from higher energy states to lowers ones within the inhomogeneously broadened DOS, were also observed in PPV polymers [23,25,26]. Since the variation of the relative molecular orientation leads to the effect of inhomogeneous broadening, the widths of the Alq3 highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) levels are significant compared to those of the system with a high structural order [27]. This leads to a broad distribution of the exciton energy levels. Because doping such a system creates additional deep trap states at the tail of the intrinsic DOS, the effect of inhomogeneous broadening is enhanced and the exciton acceptors can be incorporated as deep traps in the exciton DOS [4–7].

![Graph](image-url)

Fig. 3. Low-temperature (10K) transient luminescence intensities at several photon energies of the (a) 1% and (b) 7% C545T-doped Alq3 samples.

A dynamic scenario representing possible paths of the exciton transport (jump) among host molecules and from host molecules into the guest molecules is proposed in Fig. 4(a). Due to the inhomogeneous broadening, the exciton energy levels of the host and dopant molecules are spatially varied. Here, exciton transport (jump) from a higher-energy states down to a deeper potential minimum is indicated. At low temperatures, non-radiative recombination and thermal effect can be neglected. The exciton transport process can also be used for interpreting the fast early-stage decay on the high-energy side (curves of 2.58 eV).
Because of fast exciton out-flow, PL intensity decays fast on the high-energy side. Hence, it was proposed that the delayed slow rise was due to the exciton jump process from a host molecule to either a deeper intrinsic site within the intrinsic DOS or a dopant molecule, that is, the exciton capture process from higher-energy states into deeper localized states. The localized states are located at the tail of the intrinsic DOS distribution and often referred to as deep site traps. Noted that the dynamic scenario proposed here is more complicated than the conventional Förster energy transfer, but not contrary to it.

The temporal behavior of several emission photon energies at 10K of the 7% C545T-doped Alq3 film are shown in Fig. 3(b). Since the depopulation of the high-energy states is mainly due to downward hopping, the curve corresponding to 2.48 eV shows a fast exponential decay. At energies below the luminescence center, the transient excitation density is dominated by “filling-up processes” due to exciton hopping downward from higher energy states. Although low-energy shoulders were observed in the PL spectra, distinct delayed maxima in the low-energy curves such as 2.13, 2.21, and 2.29 eV were absent. Hence, an additional exciton relaxation channel should be considered. Because the aggregation-caused shoulders are on the low-energy sides of the PL spectra, the average potential levels of the aggregations were lower than those of the dopants sites. This implies that the aggregations could trap carriers more easily than the lower-energy states of the dopants sites could. Therefore, the absence of a distinct delayed maximum is due to the competition between the exciton capture into aggregations and the lower-energy localized states. A dynamic scenario representing the competition of the exciton transport into the deep site traps (localized states) and aggregations is shown in Fig. 4(a). The aggregations could easily trap excitons for self-quenching and enhance nonradiative recombination.

The multiple exponential curves could be fitted well with the bi-exponential model (except the delayed slow rise duration):

\[ I(t) = A_1 \exp(-t / \tau_1) + A_2 \exp(-t / \tau_2) + I_0 \]  

where \( \tau_1 \) and \( \tau_2 \) are the early stages (fast) and extended (slow) decay times, respectively, and \( A_1 \) and \( A_2 \) are the contribution of the corresponding parts to the total PL intensity. \( I_0 \) is the
background intensity. Because the amplitude fractions of $A_1$ for all PL decay profiles are over 80%, the discussion is focused on the early-stage decay times. Figure 5 shows the early-stage decay times as a function of photon energy of the four samples. On the high-energy side, the early-stage decay time can be shorter than 500 ps. Besides exciton recombination, exciton transport processes from higher-energy states into lower-energy localized states must be considered to explain such a short decay time. In addition, the early-stage decay times increase with decreasing emission photon energy for the all samples. This is a typical characteristic of a dynamic hopping process within the inhomogeneously broadened DOS in organic semiconductors [23,25,26]. Within the exciton hopping model, strongly (lower-energy) localized excitons decay primarily via radiative recombination while weakly (higher-energy) localized excitons exhibit a decreased decay time due to the additional channel of downward hopping to lower-energy sites. In addition, a corresponding probability distribution, $P(E)$, of the exciton levels for the host and guest molecules are shown in Fig. 4(b). The proposed picture was modified from the energy diagram of the PPV light emitting diodes [28]. Due to an inhomogeneity of the local molecular environment, the distributions of the HOMO and LUMO levels lead to a broad energy distribution of the exciton energy levels. The energy distribution can be generally approximated by a Gaussian DOS distribution [28]. The continuous distributions of deep site traps and/or dopants are located at the tail of the intrinsic DOS. Discrete defect states due to chemical impurities, dopant aggregation, and structural defects are also shown below the intrinsic DOS. In the highly-disordered system [4,8], the interaction of dopant ions with carriers localized in intrinsic hopping sites further increases the energy disorder and broadens the deep tail of the DOS distribution.

![Fig. 5. Calibrated early-stage decay times as functions of photon energy of the four samples. The dotted curves represent the fitted results from using Eq. (3).](image)

In a previous study, the current-voltage ($J-V$) characteristics of the C545T-doped OLEDs could fit well with the power law $J \sim V^m$ ($m>2$) (not shown here) [1]. Therefore, the carrier transport behaviors can be described by the trapped-control mode, and the tail state distribution can be approximated by the exponential trap distribution [17–20]. As shown in Fig. 4(b), the exciton energy levels show a Gaussian DOS distribution with an exponential distribution for the tail states as:
where $H_t$ is the density of traps, and $E_t$ is the characteristic constant of the distribution [17–20]. $E_t$ can also be referred to as the localization depth ($E_0$) in the tail states. In addition, if the trap states obey the exponential distribution, and if the radiative recombination lifetime ($\tau_{\text{rad}}$) does not change with emission energy, the observed early-stage decay times $\tau(E)$ can be fitted well with the following equation [29]:

$$
\tau(E) = \frac{\tau_{\text{rad}}}{1 + \exp[(E - E_m) / E_0]}
$$

which includes pathways for either exciton recombination or downward transport. In Eq. (3), $\tau_{\text{rad}}$ is the radiative recombination lifetime and $E_0$ is the localization depth in the tail states. $E_m$ is the characteristic energy at which the recombination rate equals the transfer rate. The decay channel is predominantly radiative for lower-energy ($E < E_m$) excitons, while higher-energy ($E > E_m$) excitons exhibit a shorter decay time due to downward transfer to low-energy sites. A diagram of the exciton energy relaxation in the inhomogeneously broadened DOS is shown in Fig. 4(b). Characteristic energy ($E_m$), PL peak energy ($E_{PL}$), and localization depth ($E_0$) are also indicated. With the assumption of an exponential distribution for the tail states, these parameters associated with exciton energy relaxation and localization can be quantitatively determined. Although Eq. (3) is seldom used in organic materials, the exponential distribution for the tail states makes it applicable in doped OLEDs. The solid curves in Fig. 5 represent the fitted results from using Eq. (3).

Figure 6 shows the fitted results of the parameter values $\tau_{\text{rad}}$, $E_0$, $E_m$, and $E_{PL}$. $\Delta E(=E_m-E_{PL})$ is defined as the energy difference between $E_m$ and $E_{PL}$. As shown in Fig. 6(a), $E_m$ and $E_{PL}$ decrease with increasing dopant concentration. With a higher dopant concentration, the fluctuating potential level effectively became lower and the exciton transport process from higher-energy states down to lower-energy ones was enhanced. It was noted that $E_{PL}$ shows slight dependence on the dopant concentration while $E_m$ strongly depends on the dopant concentration. Although a smaller amount of dopant concentration may not change the PL peak energy much, it can enhance the degree of disorder and greatly affect the exciton transport, energy relaxation, and recombination dynamics. Also, in the lightly-doped sample, $E_{PL}$ is far below $E_m$ and $\Delta E$ becomes larger. These observations suggest that the decay channel for excitons with energy near $E_{PL}$ is dominated more by exciton recombination than by exciton transport. The enhanced exciton recombination in the lightly-doped sample implies the best luminescence efficiency among the four samples.

In addition, as the dopant concentration increased, the localization depth $E_0$ of the tail states increased. The fitted values of $E_0 = 40-120 \text{ meV}$ in Fig. 6(b) are much higher than those of the disordered alloy CdSe (12.2 meV) [29] and III-Nitride semiconductor (7-34 meV) [30,31]. This indicates a strong localization effect in such doped organic semiconductors. Due to inhomogeneous broadening of the DOS and a larger exciton binding energy of organic materials, a larger localization depth and a stronger localization effect in such disordered organic semiconductors were expected. With higher dopant concentrations, the random distributions of dopant ions as well as dopant aggregations made the potential level more varied. In other words, dopants enhanced the energy disorder as well as the degree of localization. These arguments are consistent with the previous results of larger SSs, red-shifted PL peak position, and material characterizations of the highly-doped sample. Furthermore, as shown in Fig. 6(c), $\tau_{\text{rad}}$ decreased with increasing dopant concentration. Because the aggregation-caused potential minimums could easily trap the carriers for nonradiative recombination, the radiative recombination lifetime decreased. The absence of a delayed slow rise in the highly-doped sample also can support this argument.
Fig. 6. Fitted results for the following parameters: (a) $E_m$ (the characteristic energy at which the recombination rate equals the transfer rate) and $E_{PL}$ (PL peak energy); (b) $E_0$ (localization depth in the tail states) and $\Delta E$ ($= E_m - E_{PL}$); (c) $\tau_{rad}$ (radiative recombination lifetime).

4. Conclusions

In summary, the exciton dynamics of transport, energy relaxation, and localization in disordered C545T-doped Alq3 organic semiconductors were reported. A dynamic scenario representing possible paths of the exciton transport (jump) among host molecules and the competition of the exciton transport from host molecules into the deep site traps (localized states) and aggregations was proposed to elucidate the recombination dynamics in disordered C545T-doped Alq3 organic semiconductors. Because the carrier transport behaviours of C545T-doped Alq3 OLEDs can be described by the trapped-control mode, the tail state distribution can be approximated by the exponential trap distribution. With the approximation of an exponential distribution for the tail states, the characteristic energy ($E_m$), radiative recombination lifetime ($\tau_{rad}$), and localization depth ($E_0$) associated with exciton energy relaxation and localization can be quantitatively determined. The much larger $E_0$ (40–120 meV) than other disordered semiconductors (2–34 meV) indicates a strong localization effect in such doped organic semiconductors. Also, the strong dependence of $E_m$ on the dopant concentration shows that a relatively small dopant concentration can enhance the degree of disorder and greatly affect the recombination dynamics. In addition, the observed optical properties and dynamic scenario of C545T-doped Alq3 films are found to be consistent with the carrier transport and recombination dynamics of C545T-doped Alq3 OLED devices. The results of this investigation provide important information for operation mechanisms and device designs of OLEDs.
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