Chapter 2

Charge transport models for disordered organic systems

Summary

The charge carrier mobility in organic optoelectronic devices remains by far lower than that of conventional inorganic devices.\(^1\) This must be ascribed to the specific charge transport mechanism present in organic materials. We present two theoretical models which are frequently used to analyze the charge transport in polymer based LEDs and FETs: the hopping in a Gaussian DOS is applied to explain the field and temperature dependence of the carrier mobility in LEDs, while the hopping in an exponential DOS explains the gate voltage and temperature dependence in FETs. In fact, because the polymers characterized in these devices belong to the same class of disordered $\pi$ conjugated systems, one unified description should be used to describe their electrical transport characteristics.

\(^1\)However, as argued in Chapter 1 organic semiconductors possess a number of characteristics which make it worthwhile to study them.
2.1 Introduction

An ideal crystal has a three-dimensional architecture characterized by the infinite repetition of identical structure units in space. Its structure can be described in terms of a lattice characterized by long-range order and strongly coupled atoms [1]. For silicon or germanium this strong coupling results in the formation of long-range delocalized energy bands separated by a forbidden energy gap [1]. Charge carriers added to the semiconductor move in these energy bands with a relatively large mean free path. Carrier scattering significantly affects the carrier mobility, which depends on the conductivity effective mass of electrons and the temperature. Carrier mobility in the order of $10^{-1} \text{ m}^2/\text{Vs}$ is reported for pure inorganic semiconducting crystals such as silicon or germanium. In organic crystals, such as pentacene, the molecules are held together by weak van der Waals or London forces. This weak coupling results in a narrow width for the valence and conduction bands and the band structure can be easily disrupted by introducing disorder in the system. Although organic molecular crystals still exhibit band conduction, excitations and interactions localized on individual molecules play a dominant role. Their mobility, in the order of $10^{-3} \text{ m}^2/\text{Vs}$, is significantly lower than those of their inorganic counterparts.

By contrast, conjugated polymers do not have a well-ordered structural configuration as crystals. The conjugation of the polymer backbone is disrupted by chemical or structural defects, such as chain kinks or twists. Experimentally, it has been found that the charge carrier mobility in these materials is in the range of $10^{-12} - 10^{-10} \text{ m}^2/\text{Vs}$ for polymer light-emitting diodes and $10^{-8} - 10^{-5} \text{ m}^2/\text{Vs}$ for polymer field-effect transistors. This is orders of magnitude lower than the mobility determined for organic crystals. Over the past decades intense research has been carried out in order to explain the transport of charge carriers in disordered polymer semiconductors which would justify such low mobility. There are several transport models showing good agreement with the electrical measurements for some particular systems, but no complete solution is available due to the diversity and complexity of these systems. Here, we present the most common transport models.

Disorder induced localized states

The absence of an ideal 3D periodic lattice in disordered polymer semiconductors complicates the description of charge transport processes in terms of standard semiconductor models. Because of their spatial and energetically disordered configuration, these systems have no translation symmetry. The concept of band conduction by free charges does not apply. Instead, the formation of localized states, $N = N(E)$, is enhanced and a different theoretical approach is required. In order to participate to the transport, the charge carriers must hop between these localized states (inter- or intra-chain transitions). This usually leads to a very low carrier mobility. To overcome the energy difference between two localized states, the carriers absorb or emit phonons. This process of phonon-induced hopping was suggested by Conwell [2] and Mott [3] in connection with metallic conduction in inorganic semiconductors, and later by Pines, Abrahams and Anderson [4] for electron relaxation processes in sili-
Mott discusses the hopping transport in a constant density of states (DOS), in which he argues that the hopping over long distances and hopping to high energies are equally important. In such a system the conductivity varies with temperature according to
\[ \sigma \propto \exp \left[ -\left( \frac{T_1}{T} \right)^{1/4} \right] , \]
where \( T_1 = \frac{128}{9\pi a^3 N_F k_B} \), \( N_F \) is the density of states at the Fermi level and \( a \) the size of the localized states [5]. Later, Miller and Abrahams proposed a hopping model based on a single-phonon jump rate description [6]. Their evaluation was made in the case of a lightly doped semiconductor at a very low temperature. The localized states were shallow impurity levels. The energy of these levels stands in a narrow range so the probability for an electron on one site to find a phonon to jump to the nearest site is high. The hopping rate of carriers from occupied \( i \) to unoccupied \( j \) localized donor states depends on the height of the energetic barrier \( E_j - E_i \) and the distance \( R_{ij} \) between the states \( i \) and \( j \):

\[
\nu_{i\rightarrow j} = \nu_0 \exp \left(-2\gamma R_{ij}\right) \begin{cases} 
\exp \left(-\frac{E_i-E_j}{k_B T}\right) & \text{for } E_j > E_i \\
1 & \text{for } E_j < E_i
\end{cases}
\]

where the pre-factor \( \nu_0 \) is the attempt-to-hop frequency, \( \gamma \) is the inverse localization length, \( a \) is the average lattice distance, and \( k_B \) is the Boltzmann constant. The first exponential term from Eq. 2.1 represents the tunneling probability and the second exponential term accounts for the temperature dependence of the phonon density. When this model is applied to polymer semiconductors, the following assumptions are made: the conjugated segments of the polymer play the role of nearly isolated states and Eq. 2.1 is still valid at high temperatures [6].

The polaron model

The polaron model was first introduced in the case of inorganic crystals [7], and has later been used to explain the charge transport in molecular crystals [8] and conjugated polymers [9]. This transport model takes into account the strong electron-phonon interaction.

A polaron is basically a quasiparticle which results from the combination of a charge carrier with a lattice deformation induced by its charge. The transition rate for polarons as determined by Marcus is given by [10]:

\[
\nu_{i\rightarrow j} \propto \frac{1}{\sqrt{E_r T}} \exp \left[ -\frac{(E_j - E_i + E_r)^2}{4E_r kT} \right] \quad (2.2)
\]

where \( E_r \) is the intramolecular reorganization energy. The charges moving by thermally activated hops between adjacent sites have a mobility which is field \( (F) \) and temperature \( (T) \) dependent [10, 11]:

\[
\mu = \mu_0 \exp \left[ -\frac{E_r}{4kT} - \frac{(aF)^2}{4E_r kT} \right] \cdot \sinh \left( \frac{aF}{2kT} \right) \quad (2.3)
\]
where $\mu_0$ is slightly temperature dependent. However, using Marcus theory the polaron contribution to the activation of the mobility is insignificant. The activation of the mobility using this model amounts to 25-75 meV [12], while using the disordered model the activation energy amounts to 420 meV [13].

Another model that takes into account the strong coupling of charge carriers with the lattice is the Su-Schrieffer-Heeger (SSH) theory [14], which describes the electronic structure of conjugated polymers. This model is based on the concept of bond alteration along a perfect conjugated polymer chain with weak interchain coupling. Adding a charge to the polymer chain leads to a profound change in its geometrical structure characterized by a permutation of the bond alteration over a certain number ($\approx 3 - 5$) monomeric units. The $\pi$-electrons are treated in a tight-binding approximation. The main omission of the SSH model is that it does not consider the electron-electron and electron-hole interactions, which play an important role in the transport and recombination of charge carriers.

The multiple trapping and release model

Another model used to account for the low mobility in amorphous organic materials is the multiple trapping and release model. In this model a narrow band is associated with a high concentration of trap levels. Traps are levels localized at lattice defects or impurities in which the charge carriers are immobilized. These traps can be deep traps, which are located near the center of the band gap, or shallow traps, which are located close to the conduction or valence band. Developed for hydrogenated amorphous silicon (a-Si:H) by Le Comber and Spear [15], the multiple trapping and release model has been used more recently by Horowitz et al. [16] to explain the transport in sexithiophene FETs. This model assumes an exponential distribution of gap states. The charges injected or the charges which are already present in the organic semiconductor are trapped into localized states with a probability close to one and then released through a thermally activated process. The drift mobility $D$ is given by:

$$\mu_D = \mu_0 \alpha \exp \left( - \frac{E_T}{k_B T} \right)$$

(2.4)

where $\mu_0$ is the mobility at the band edge, $\alpha$ is the ratio between the effective density of states at the transport band edge and the density of traps, and $E_T$ is the energy of the trap state. It has been demonstrated that the transport of carriers depends on the energy level of the trap states, the temperature and the voltage applied [16].

2.2 Charge carrier transport models for polymer LEDs and FETs

A semiconducting polymer is not a perfect conjugated system, because its twisted and kinked chains and chemical defects cause conjugation breaks (Figure 2.1). Due to the
variation in the conjugation lengths and in the interaction energies the semiconductor cannot simply have two delocalized energy bands separated by an energy gap. Instead, an energetic spread of the charge transport sites will be present, often approximated in shape by a Gaussian density of states (DOS). This shape is supported by the observation of Gaussian shaped absorption spectra of polymer materials \([13]\). The shape of the DOS is important for the description of the charge transport because it reflects the disorder of the system.

**Figure 2.1:** (a) Schematic view of polymer chain segments broken by defects, kinks between which the charge carriers hop. (b) Representation of the energy distribution of the localized states, which is approximated by a Gaussian distribution for the LUMO and HOMO levels.

### 2.2.1 Gaussian density of states

Bässler \([13]\) proposed in 1993 a charge transport model for disordered organic systems. He assumes that electron-phonon coupling is sufficiently weak so that the polaronic effects can be neglected, and the hopping rates can be described by the Miller-Abrahams formalism (Section 2.1). The charges hop in a regular array of hopping sites. In this way both positional disorder (fluctuation in inter-site distance) and energetic disorder (fluctuation in site-energy) are introduced. In this model, the energy distribution of localized states can be approximated by a Gaussian function \([13]\):

\[
DOS_{\text{Gauss}} = \frac{N_t}{(2\pi\sigma_{\text{DOS}})^2} \exp\left(-\frac{\epsilon^2}{2\sigma_{\text{DOS}}^2}\right)
\]  

(2.5)

where \(N_t\) is the total density of sites, \(\sigma_{\text{DOS}}\) is the width of the Gaussian density of states (DOS) and the energy \(\epsilon\) is measured relative to the center of the DOS. The choice for this particular DOS shape is supported by the observation that the
absorption spectra of disordered organic materials usually have Gaussian profiles [17] and by the fact that coupling between a charge carrier and a random distribution of static or induced dipoles leads to a Gaussian DOS function [18].

The charge transport in the Gaussian disorder model (GDM) cannot be solved analytically and therefore an alternative approach of Monte Carlo simulations has been applied [13,19,20]. Using the hopping rate from the Miller-Abrahams formalism, the Monte Carlo simulations revealed that carriers (in this case the electrons) with an arbitrary energy within a Gaussian DOS relax to an equilibrium level $-\sigma_{DOS}^2/k_BT$ below the center of the DOS distribution and the required energy to participate to the transport in the transport level located at $-(5/9)\sigma_{DOS}^2/k_BT$ (Figure 2.2). This gives rise to the dependence $\mu(T) = \mu_0 \exp \left[-\left(\frac{2\sigma_{DOS}}{3k_BT}\right)^2\right]$. But the hopping mobility must depend also on the electric field since the average barrier height for energetic uphill jumps in field direction is reduced [13]. On the basis of the Monte Carlo simulations, the charge carrier mobility is temperature- and field-dependent, and in the limit of high electric fields is given by [13]:

$$\mu_{GDM} = \mu_0 \exp \left[-\left(\frac{2\sigma}{3k_BT}\right)^2\right]$$

\[
\begin{cases} 
\exp \left[ C \left( \frac{\sigma}{k_BT} \right)^2 - \Sigma^2 \right] \sqrt{F} & \text{for } \Sigma \geq 1.5 \\
\exp \left[ C \left( \frac{\sigma}{k_BT} \right)^2 - 2.5 \right] \sqrt{F} & \text{for } \Sigma < 1.5 
\end{cases} 
\]

where $\mu_0$ is the mobility in the limit $T \to \infty$, with values between $10^{-6}$ and $10^{-5}$ m$^2$/Vs, $C$ is a constant that depends on the site spacing, and $\Sigma$ is the degree of positional disorder. A consequence of hopping in a Gaussian DOS is the non-Arrhenius behavior of the mobility [13].

![Figure 2.2](image)

**Figure 2.2:** (a) The transport level located at $-(5/9)\sigma_{DOS}^2/k_BT$ and the equilibrium level located at $-\sigma_{DOS}^2/k_BT$ in a Gaussian DOS. (b) Representation of the energetic uphill jumps in the direction of the field. This representation is given for electrons.
Because the results of simulations performed within the frame of the standard Gaussian disorder model can explain the experimental results only at high fields (> \(10^8\) V/m), further improvement was necessary. A spatially correlated site-energy distribution was considered [21], which means that the energies are correlated over a greater length than the distance between hopping sites. Due to the correlation of energies of adjacent sites, the field dependence of the mobility extends to lower electric fields. Spatial correlations in site-energy may arise from long-range charge-dipole interactions in the material, where the disorder is determined by the random orientations of dipole moments of nearby molecules. In this correlated disordered model (CDM), the empirical expression for the mobility is given by [22, 23]:

\[
\mu_{CDM} = \mu_0 \exp \left[-\left(\frac{3\sigma_{DOS}}{5k_BT}\right)^2\right] \\
\times \exp \left[C_0\left(\frac{\sigma}{k_BT}\right)^{3/2} - \Gamma\right] \frac{\sqrt{eaF}}{\sigma}
\]  

(2.7)

where \(C_0=0.78\), \(a\) is the intersite separation, and \(\Gamma = 2\) for organic materials. The main difference between GDM and CDM is the predicted temperature dependent field dependence. Furthermore, in contrast with GDM, CDM simulations showed a better agreement with the experimental data at low fields [22, 24].

Over the last years the CDM hopping model of charge carriers in a Gaussian DOS has been used in order to explain the experimentally observed temperature and field dependence of the hole mobility in PPV based LEDs. In order to investigate the hole mobility, diodes with one hole injecting contact and one electron blocking contact have been fabricated. Such a structure is called hole-only diode. The experimentally measured current-voltage characteristics at low electric fields of hole-only diodes show a quadratic behavior, indicating that the current is space-charge limited. Injected from the contacts the charge carriers move slow in the polymer, which leads to the build-up of space charge in the semiconductor film. From the analysis of the transient measurements for PPV, it was demonstrated that in the steady-state the hole transport is “trap-free“ [25], which means that the concentration of deep traps is small compared to the free carrier concentration [26, 27]. In this case the current density is characterized by Child’s law [27]:

\[
J = \frac{9}{8} \epsilon_0 \epsilon_s \mu \frac{V^2}{L^3}
\]

(2.8)

where \(\epsilon_0\) is the permittivity of vacuum, \(\epsilon_s\) is the relative dielectric constant of the semiconductor, \(\mu\) is the carrier mobility and \(L\) the thickness of the device. At high biases the current starts to increase more rapidly with voltage and Eq. 2.8 is no longer valid (Figure 2.3). This suggests that the mobility increases with the applied voltage. By changing the temperature, it is found that the mobility also depends on the temperature. The hole transport in PPV can be described by the combination of the SCL conduction model with a temperature and field-dependent mobility [28]:
\begin{equation}
J = e p(x) \mu_p(F(x), T) F(x)
\end{equation}

\begin{equation}
\frac{\epsilon_0 \epsilon_s}{e} \frac{dF(x)}{dx} = p(x)
\end{equation}

\begin{equation}
\mu_p(F, T) = \mu(F = 0) \exp \left( -\frac{\Delta}{k_B T} + \gamma \sqrt{F} \right)
\end{equation}

where \( p(x) \) is the density of holes at position \( x \) in the semiconductor film, \( \mu(F = 0) \) is the zero-field mobility, \( \Delta \) is the zero-field activation energy, and \( \gamma \) is the field dependence parameter. The empirical equation which gives the temperature and field dependence of the mobility (Eq. 2.11) was noticed for the first time in poly(N-vinyl carbazole) by Gill in 1972 [29]. Since then this dependence was very often observed in disordered organic semiconductors [28, 30–32]. This equation system can be solved numerically for any given value of \( J \). We present here the results obtained in Ref. [28]. We use the above described model to explain the \( J-V \) characteristics for a PPV derivative based hole-only diode (Figure 2.3).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2_3.png}
\caption{\( J-V \) characteristics of OC\(_1\)C\(_{10}\)-PPV hole-only diode for various temperatures. The polymer thickness is 125 nm. The dotted lines represent the prediction of the conventional SCLC model using Eq. 2.8. The solid lines represent the prediction of the SCLC model using the field-dependent mobility given by Eqs. 2.11 and 2.9 (data from Ref. [28]). The polymer is described in Chapter 3.}
\end{figure}

At low voltages the \( J-V \) characteristics are well described by the SCLC given by Eq. 2.8 (Figure 2.3 dashed lines), from which the zero-field mobility \( \mu_p(0) = 5 \times 10^{-11} \) m\(^2\)/Vs is determined. At high voltages the SCL model with field-dependent mobility is used, giving an accurate description of the experimental data (Figure 2.3 solid lines). From the modeling the field coefficient \( \gamma = 5.4 \times 10^{-4} \) (m/V)\(^{1/2} \) and the activation energy of the mobility \( \Delta = 0.48 \) eV have been determined. In most experiments,
the temperature range is limited. Consequently it is difficult to discriminate between an \( \ln(\mu) \propto -(\sigma/k_B T)^2 \) dependence (Eq. 2.6) and the Arrhenius behavior \( \ln(\mu) \propto -(\Delta/k_B T) \) (Eq. 2.11).

### 2.2.2 Exponential density of states

The hopping model proposed by Miller and Abrahams was further extended to the so-called variable range hopping model in which it is assumed that the localized states are spread over the entire energy gap [5]. This model suggests that charge carriers may either hop over a small distance with a high activation energy or hop over a long distance with a low activation energy. Subsequently, Monroe developed a transport model for the transport of photoexcited carriers within an exponential density of states (DOS) [33]. He describes the transport of charges in the band tail when hopping in addition to thermal excitation to the band edge is included.

The variable range hopping was further developed by Vissenberg and Matters in order to explain the charge transport in polymer FETs [34]. This transport model takes into account the filling of localized states with charge carriers in contrast to the one developed by Bässler which is a one particle model. The model predicts that at low carrier densities and low temperatures, the transport properties are determined by the tail states of Gaussian DOS, which is approximated by an exponential DOS [34]:

\[
DOS_{\text{expon}} = \frac{N_t}{k_B T} \exp\left(\frac{\epsilon}{k_B T_0}\right) \tag{2.12}
\]

where \( N_t \) is the number of states per volume unit, \( T_0 \) is the width of the exponential DOS, and \( \epsilon \) the level energy. It is considered that the energy distribution of the carriers at equilibrium is given by the Fermi-Dirac distribution. If the system is filled with a charge carrier density, \( \delta N_t \), which occupies a small fraction \( \delta \in [0, 1] \) of the localized states, the position of the Fermi level is fixed by the condition:

\[
\delta \approx \exp\left(\frac{E_F}{k_B T_0}\right) \Gamma\left(1 - \frac{T}{T_0}\right) \Gamma\left(1 + \frac{T}{T_0}\right) \tag{2.13}
\]

where approximation \( -E_F >> k_B T_0 \) has been used, meaning that most carriers occupy the sites with energy \( \epsilon << 0 \), and \( \Gamma(a) = \int_0^\infty dx \exp(-x)x^{a-1} \). This condition is fulfilled when \( \delta \) is low and \( T < T_0 \). For temperatures \( T \geq T_0 \) the function \( \Gamma(1 - T/T_0) \) diverges and the assumption that only the tail of the DOS is important is no longer valid. The conductance of the system is given by the following equation:

\[
G_{ij} = G_0 \exp(2\alpha R_{ij}) \exp\left(\frac{|E_i - E_F| + |E_j - E_F| + |E_i - E_j|}{2k_B T}\right) \tag{2.14}
\]

where \( G_0 \) is a prefactor for the conductivity, \( \alpha \) the effective overlap of electronic wave functions of the sites \( i \) and \( j \) and \( R_{ij} \) the distance between the sites.

Using the percolation theory [35], an expression for the conductivity can be derived as a function of the occupation fraction \( \delta \) and the temperature \( T \) [34]:
\[ \sigma (\delta, T) = \sigma_0 \left( \frac{\delta N_i (T_0/T)^4 \sin \left( \frac{\pi T}{T_0} \right)}{(2\alpha)^3 B_c} \right)^{T_0/T} \] (2.15)

where \( \sigma_0 \) is a prefactor for the conductivity, and \( B_c \) is the critical number for the onset of percolation. For three-dimensional amorphous systems \( B_c \approx 2.8 \) [36]. The conductivity expressed by Eq. 2.15 has an Arrhenius-like temperature dependence \( \sigma \propto \exp \left[ -E_a / k_B T \right] \) explained by the fact that in an exponential DOS the hopping can be described in terms of activation from the Fermi level to a specific transport level [33]. Moreover, the conductivity increases superlinearly with the charge carrier density \( \sigma \sim \delta^{T_0/T} \). This is due to the fact that by increasing the carrier density the states are filled and an activated jump to the transport energy is facilitated.

When a small drain bias, \( V_d \), is applied to the \( p \)-type organic FET, the current that flows in the conducting channel is small and ohmic and the conductivity of the semiconductor is [37]:

\[ \sigma \approx \left( \frac{L}{Wh} \right) \left. \frac{I_d}{V_d} \right|_{V_g=0, V_d \rightarrow 0} \] (2.16)

where \( L \) and \( W \) are the channel length and width, respectively, and \( h \) is the thickness of the semiconductor. If now a negative gate voltage, \( V_g \), is applied to the gate, the charges accumulate in the active semiconducting channel and the drain current increases due to the "field-effect". The total amount of induced charges in the accumulation channel is \( C_i V_g \). By applying now a small drain voltage, \( V_d \), the increase of the current in the accumulation channel is [38]:

\[ \delta I_d = \frac{W}{L} C_i V_d \delta V_g \mu_{FET} (V_g) \] (2.17)

Here the gradual channel approximation has been used, which means that \( V_d << V_g \) such that the potential drop between source and drain can be neglected. Furthermore, it should be noted that the use of the total amount of induced charges \( (C_i V_g) \) in Eq. 2.17 is only valid when all charge carriers have the same mobility. But in disordered organic FETs the charge carrier density decreases from the semiconductor/insulator interface into the bulk (See Figure 1.4). According to Eq. 2.13, the occupation \( \delta(x) \) depends on the gate induced potential \( V(x) \) which depends on the distance:

\[ \delta(x) = \delta_0 \exp \left( \frac{qV(x)}{k_B T_0} \right) \] (2.18)

where \( \delta_0 \) is the carrier occupation far from the semiconductor/insulator interface. In this situation the source-drain current must be calculated over the entire accumulation channel using the following expression [34]:

\[ I_d = \frac{WV_d}{L} \int_0^d \sigma (\delta(x), T) \, dx \] (2.19)
From Eqs. 2.15 and 2.19 the following expression for the field-effect current is determined [34]:

\[
I_d = \frac{W V_d \varepsilon_s \varepsilon_0 \sigma_0}{L q} \left( \frac{T}{2T_0 - T} \right)
\times \sqrt{\frac{2k_B T_0}{\varepsilon_s \varepsilon_0}} \left[ \left( \frac{T_0}{T} \right)^4 \sin \left( \frac{\pi T}{T_0} \right) \right]^{T_0/T}
\times \left[ \sqrt{\frac{\varepsilon_s \varepsilon_0}{2k_B T_0}} \left( \frac{C_i (V_g - V_{so})}{\varepsilon_s \varepsilon_0} \right) \right]^{2T_0/T - 1}
\]

(2.20)

where \( q \) is the elementary charge, \( \varepsilon_s \) is the relative dielectric constant of the semiconductor, \( \varepsilon_0 \) is the permittivity of vacuum, and \( V_{so} \) is the switch-on voltage of the transistor. For an unintentionally doped polymer \( V_{so} \) is determined by fixed charges in the insulator layer or at the semiconductor/insulator interface. In this case \( V_g \) becomes \( V_g - V_{so} \). Eq. 2.20 has been used successfully to model the transfer characteristics of organic FETs [39].

Here we present the modeling of a polythiophene derivative FET (Figure 2.4). The transistor was measured in the linear regime \( (V_d = -2 \, \text{V}) \) and has the following dimensions: \( W = 2500 \, \mu\text{m}, \, L = 10 \, \mu\text{m} \). The fit parameters are \( T_0 = 425 \, \text{K}, \, \sigma_0 = 1.6 \times 10^6 \, \text{S/m} \) and \( \alpha^{-1} = 0.16 \, \text{nm} \) [39]. We used \( \varepsilon_s = 3 \). Good agreement between the experimental data and the model described here has been obtained.

**Figure 2.4:** \( I_d \) versus \( V_g \) of P3HT field-effect transistor for various temperatures. The solid lines represent the prediction of the Vissenberg model using Eq. 2.20. The inset shows the chemical structure of P3HT.
2.2.3 Summary

We presented two theoretical models which are frequently used to analyze the charge transport in polymer based LEDs and FETs: hopping in a Gaussian DOS is applied to explain the field and temperature dependence of the carrier mobility in LEDs, while the hopping in an exponential DOS explains the gate voltage and temperature dependence in FETs. In fact, because the polymers characterized in these devices belong to the same class of disordered \( \pi \)-conjugated systems, one unified description should be used to describe their electrical transport characteristics. A detailed discussion of this matter will be presented in Chapter 4.

Bibliography
