Transient I-V-Characteristics of OLEDs with Deep Traps

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Abstract

Measured current-voltage-characteristics of OLEDs show a large hysteresis for different sweep directions. To clarified this peculiarity we have carried out 2D simulations of transient current-voltage characteristics with a systematic variation of the relevant parameters to investigate this characteristics. It turns out that the transient behaviour can be explained by deep traps. Due to the high energy gap of organic materials deep traps can lie far from the bands. Further, the thermal velocity of the carriers is extremely low and consequently the time constant for trap recharging is very high. Therefore, a high delay time is necessary to measure the reverse steady-state current and to prevent the hysteresis effects.

1. Introduction

Despite of several theoretical models for organic light emitting diodes (OLEDs) [1, 2, 3, 4], there are only a few describing the influence of deep traps on the device characteristics [5, 6]. In this work we discuss the influence of deep traps on the transient current characteristics by means of experimental results and 2D simulations.

2. Experimental results

In Fig.1 the I-V-characteristics of a ITO/NPB/Ca device at different delay times and sweep directions are shown. The transition from negative to positive currents does not occur at zero voltage but

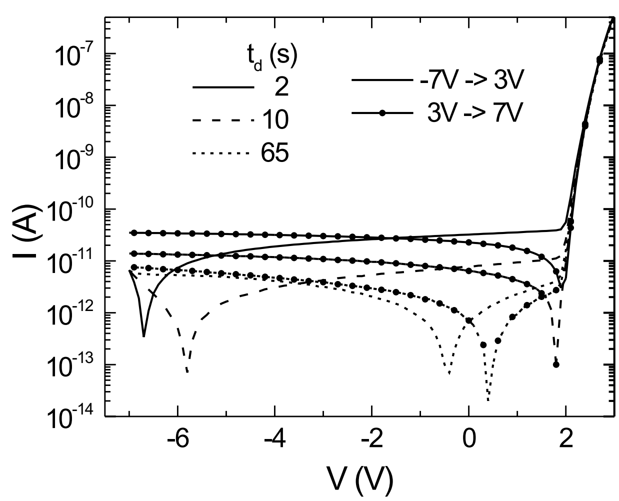

Figure 1. Current characteristics of a ITO/NPB/Ca device with a 430 thick NPB layer

at a negative voltage for the measurement from reverse to forward direction and at a positive one for the inverse direction. Further, also the reverse current for the sweep from forward to reverse direction depends strongly on the measuring velocity. The results show that delay times up to $100s$ are necessary to reach the steady-state current. The measured reverse current is higher than expected from theoretical estimates. Also, at positive voltages up to about the built-in potential of $2V$ the current is higher and there is only a little increase of the current in this region. These two effects indicate that leakage currents dominate the device current at negative and low positive voltages.

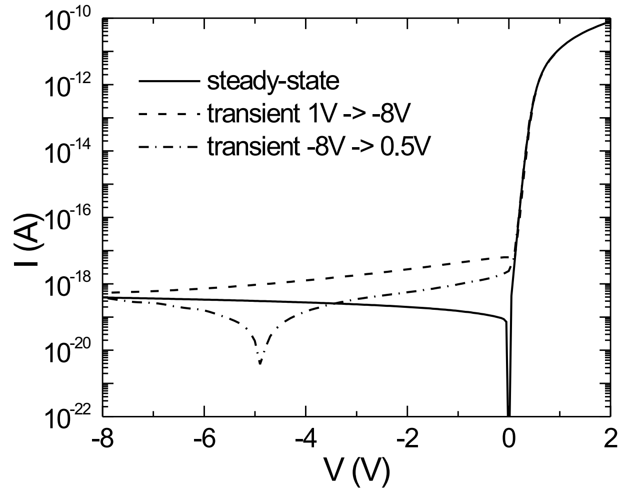

Figure 2. Transient and steady-state current characteristics of the ITO/PPVAl diode

3. Simulations with deep traps

We carried out 2D simulations for a ITO/PPV/Al structure. PPV was used to obtain sufficiently high reverse currents to prevent numerical problems as obtained for the very low theoretical reverse currents of NPB devices. The parameters of the device are the thickness $d_{dev} = 500nm$, intrinsic density $n_i = 69cm^{-3}$, band gap $E_G = 2.4eV$, affinity $\chi = 2.6eV$, mobility $\mu_p = \mu_n = 10^{-3}cm^2/Vs$, doping concentration $N_A = 10^6cm^{-3}$ and permittivity $\varepsilon_r = 3$. Traps can only influence the transient current if their occupation depends on the voltage. From first simulations we concluded that trapping/detrapping processes occur for acceptor traps with levels below the intrinsic level. Furthermore one has to consider the very low thermal velocity of the holes in organic materials [7] so that we used $N_{tA} = 10^{16}cm^{-3}$, $E_t - E_V = 0.5eV$ and $v_{th} = 10cm/s$ as trap parameters. Simulated I-V-characteristics are shown in Fig.2. The shift of the transition from negative to positive currents occurs for the simulation from reverse to forward direction but not for the inverse one. To obtain the shift to positive voltages leakage currents have to be considered. In addition the difference of the steady-state and transient curves is caused by the slow trapping and detrapping of the holes. From the selected trap parameters one obtains a time constant of approximately $25s$ for these two processes. The transient currents at a voltage of $-1V$ after a delay time of $6s$ (Fig.3) verify the theoretical estimate. For the simulation from forward to reverse direction the transient current density is higher than in the steady-state and not constant indicating that the occupation of the traps with electrons is not terminated. For the inverse sweep direction the absolute value of the transient current density is also higher than the steady-state one but the current density is negative and the diode is already in forward direction. As shown in Fig.4 during the ramp time the holes flow from anode to cathode causing a reduced depletion region and in the inverse direction again during the delay time. Only by increasing the

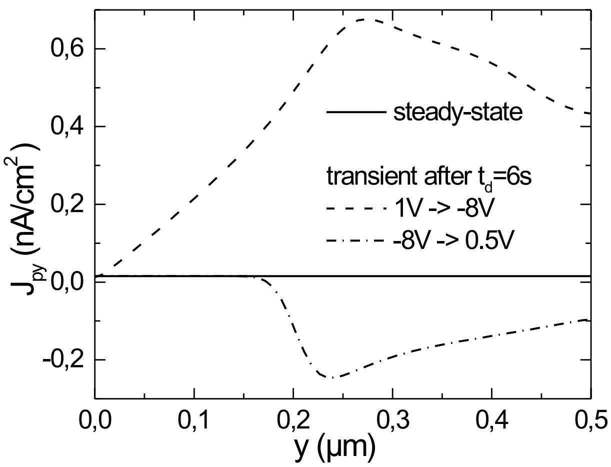

Figure 3. Transient and steady-state hole current densities for $U = -1V$ and a delay time of $6s$. Cross section in the middle from cathode to anode.

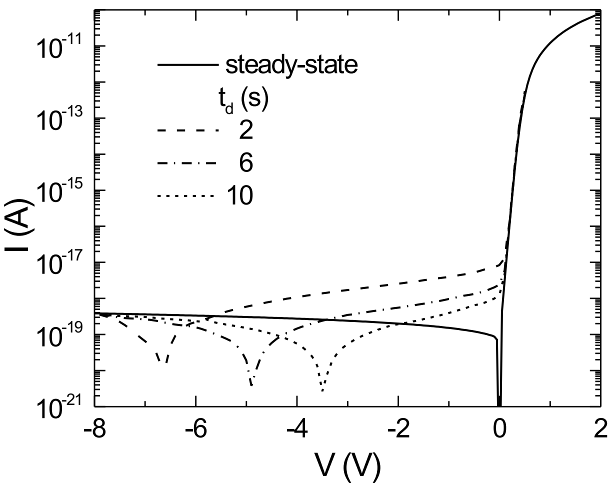

Figure 5. Current characteristics at different delay times for simulation from reverse to forward direction.

delay time, the difference between steady-state and transient concentrations is reduced for both sweep directions. Consequently the negative voltage of the transition from reverse to forward currents is reduced from $-6.6V$ to $-3.4V$ increasing the delay time from $2s$ to $10s$ (Fig.5). The curves of this figure show the same tendency as the experimental results of Fig.1 giving evidence that the slow trapping/detrapping process is the origin for the described experimental effects. Further, these effects depend on different parameters of the structure and the traps. In Fig.6 the influence of the trap level is shown. The voltage for the transition from negative to positive current depends sensitively on the trap level. Though the time constant of the trapping process increases

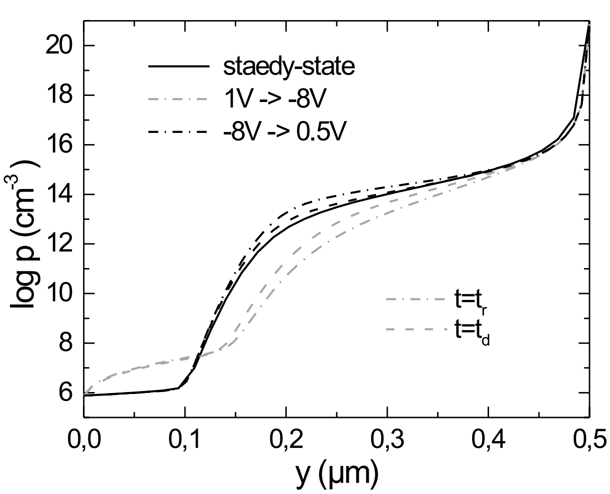

Figure 4. Hole concentration for $U = -1V$ and different times. Cross section in the middle from cathode to anode.

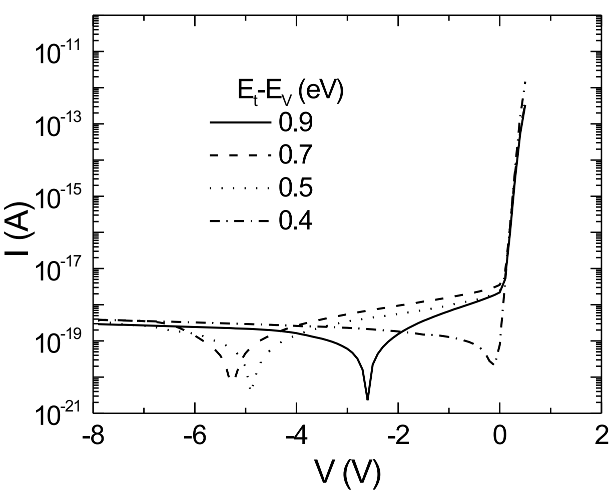

Figure 6. Current characteristics for different trap levels for simulation from reverse to forward direction.

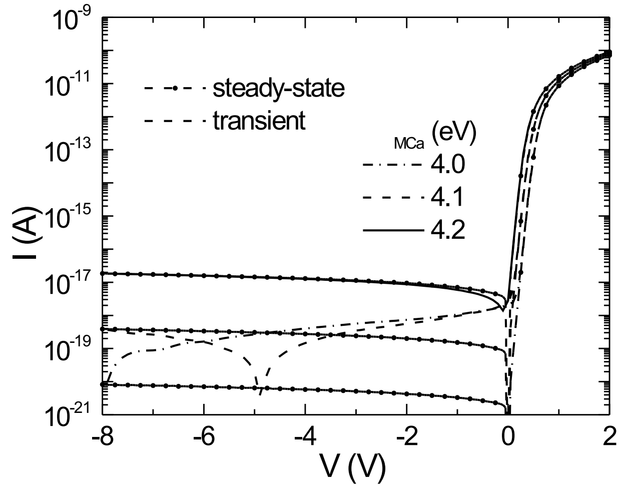

Figure 7. Current characteristics for different cathode work function for simulation from reverse to forward direction.

from $4s$ to 10^8s for levels of $0.4eV$ to $0.9eV$ the shift of the curves has a maximum for $E_t - E_V = 0.7eV$. From the occupation of the traps at different voltages (not shown here) we can conclude the concentration of the occupied traps in the depletion region depends on the trap level. For levels from $0.4eV$ to $0.7eV$ all of the traps are occupied but only a few for a level of $0.9eV$ so that the transition of the current occurs at reduced negative voltages. Fig.7 shows the influence of the cathode work function causing a variation of the reverse current. For very low currents ($\Phi_{Mcat} = 4.0eV$) the negative voltage for the transition is higher than $8V$. Increasing the work function of the cathode to $4.2eV$ the steady-state current is so high that the shift of the transition from negative to positive currents disappears. The analogous effect was obtained for different mobilities.

4. Conclusions

The results of the simulation have shown that deep traps cause the observed variation of the transition from negative to positive currents for the simulation from reverse to forward direction. For the inverse direction we have only demonstrated the variation of the reverse current but not the shift of the curves to positive voltages. In the experimental curves the current up to about the built-in voltage of $2V$ is dominated by leakage currents not included in the 2D simulation. For this reason the simulated curves do not show the shift in this sweep direction. The time constant of trapping/detrapping process is very high because of the low thermal velocity and the high energy gap causing that traps lie far from the bands. Further, this process depends sensitively on a lot of parameters as e.g. the doping concentration or the trap level. With transient simulations one can prove that the traps are responsible for the hysteresis effects but it is not possible to determine the exact parameters of the traps since there are too many different influences both of the material and the trap on the value of the transition voltage.

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