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SCIENTIFIC PAPER

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ANALYTICAL MODEL OF CARRIER MOBILITY IN A POLYMER FIELD EFFECT TRANSISTOR*

In this paper, the carrier mobility analytical model in a POFET (Polymer Field Effect Transistor) channel is proposed. The model was developed on the basis of existing models and experimental results. The proposed model is universal because it encompasses the carrier mobility dependence on temperature, electric field and trap density in the POFET channel. The model is comparatively simple, easy for application and gives valuable results. According to the presented model, simulations of mobility as a function of the parameters of interest were performed. The obtained results are shown graphically. In comparison to accessible experimental results excellent correspondence was found. This model enables the calculation of simple POFET current–voltage I (V) characteristics.

Electronic transport in organic semiconducting polymers has been studied extensively in the past decades [1–9]. Polymer materials are also considered in the optical domain as electro–optical materials (for electro–optical modulators), photodetectors and in other applications of light emission. In the last few years there were numerous studies about these materials because of their ability to transfer the charge carrier and the possibility to apply them in devices based on field effect transistors–FET. This fact is evidence that polymer electrical devices are still in the early phase of evolution as semiconducting materials were previously. Consequently, the benefits obtained by these devices are not at the same level as those obtained by still existing inorganic semiconducting materials.

However, polymer devices have a few obvious advantages in comparison to other semiconductor components. First, all polymer devices have great potential to be manufactured at low cost, because of fewer and simpler production processes than for other semiconducting devices. Second, polymer devices are more flexible materials. This possibility can be used if higher material flexibility is required. The last thing is that polymer materials can be an excellent tie of technologies between the electronic and optical domain. There is already great interest for polymer materials in optical devices. In some cases it is better to connect two polymer devices than to connect a polymer and semiconductor device.

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Considering the charge carrier transport mechanism in organic semiconductors, the existence of two extremely different transport types: dispersive (Gaussian transport) and non–dispersive transport may be seen. In this study, the model of charge carrier transport in disordered molecular solids is based on Gaussian formalism. This type of charge carrier transport will appear if the generated carrier package migrates through the bulk at constant velocity. This is the case when every charge carrier spends the same time at its own level as other charge carriers at their levels. Only thermal diffusion of the charge carrier leads to the spatial spread package of the carrier during their migration through the material. This is a statistical process and the resulting carrier package will have a Gaussian distribution of state (DOS).

MOBILITY MODEL

The POFET cross–sectional view, with the active layer made of polymer material, is shown in Figure 1a. The structure formulas of four polymers considered in this paper are shown in Figure 1b. The mode of deposition of the thin polymer layer strongly affects its structure, which has further great consequences on the electric characteristics of POFET [10].

During migration of the charge carrier through the material a constant current can be noted. When the carriers reach the collector electrode the current decreases. This is proof of charge carrier package diffusion spreading during their migration through the bulk (Figure 2).

Due to excellent film–forming properties, the following four polymers were used: (1) poly–spiro–bifluorene polymer (PSBF), (2) *N,N'*–diphenyl–*N,N'*–bis–(3–methylphenyl)–1,1'–biphenyl–4,4'–diamine (TPD), (3) poly(phenylene vinylene) (PPV), (4) poly(9–vinyl carbazole) (PVK) (Figure 1b). The following experimental results were observed [11]: (1) the mobility is

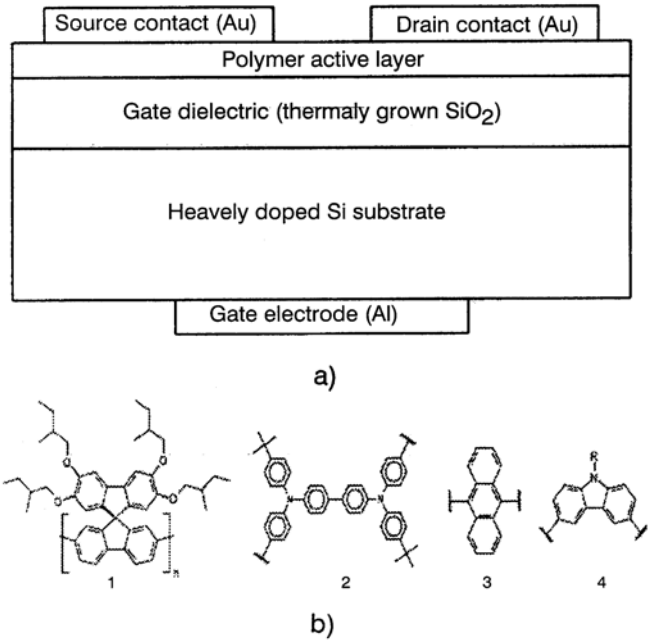

Figure 1. a) POFET Cross–section; b) Structural formulas of the considered polymers

strongly dependent on temperature; (2) Poole–Frenkel's type of mobility dependence on electric field, $\log \mu \propto \beta E^{1/2}$; (3) decrease of the slope β when the temperature increases; (4) a slick region of non–dispersive TOF (time–of–flight) signals; (5) erratic spreading of the TOF signal tail; (6) mobility temperature dependence without the applied electric field on $1/T^2$; (7) change of the TOF signal slope below the critical temperature (the signals become dispersive).

According to the model and experimental results accessible from the literature, a carrier mobility analytical model in polymer materials was proposed. The mobility dependence on temperature was calculated for different on and off disorder parameters. In all cases the mobility approached $\log \mu \propto \beta E^{1/2}$ for high fields ($E \geq 7 \times 10^5$ V/cm), which is in agreement with Poole–Frenkel's behavior. Combining all possibilities, the following universal equation for the mobility dependence on temperature and electric field can be written [12]:

$$\mu(\sigma,\Sigma,T,E) = \mu_0 \times \exp\left[-\left(\frac{2\sigma}{3kT}\right)^2\right] \times$$

$$\times \exp C\left[\left(\frac{\sigma}{kT}\right)^2 - \Sigma^2\right]\sqrt{E} \qquad (1)$$

Equation (1) takes into account the energetic disorder σ and position disorder Σ, where C is an empirical constant (typical $C = 2.9 \times 10^{-4}$ $(\mathrm{cm}/V)^{1/2}$). It can be mentioned that without an electric field equation (1) becomes:

$$\mu = \mu_0 \times \exp\left[-\left(\frac{T_c}{T}\right)^2\right] \qquad (2)$$

where T_c is the characteristic temperature at which the curve changes its slope. The connection with σ of DOS can be expressed in the following form:

$$kT_c = \frac{2\sigma}{3} \qquad (3)$$

The mobility dependence on temperature without an applied electric field is given by:

$$\mu(\sigma,E=0) = \mu_0 \times \exp\left[-\left(\frac{2\sigma}{3kT}\right)^2\right] \qquad (4)$$

Considering the mobility model accessible from the literature, the following universal model is proposed for charge carrier mobility:

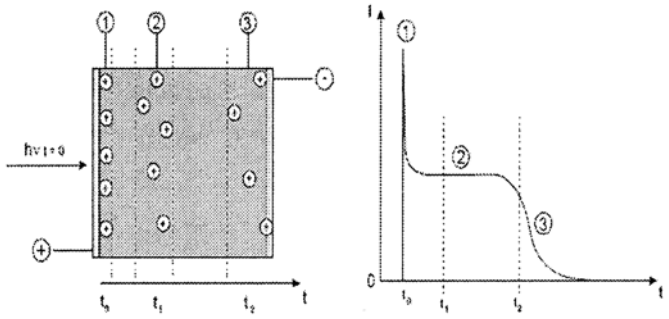

Figure 2. Charge carrier package during Gaussian transport and the corresponding current characteristic

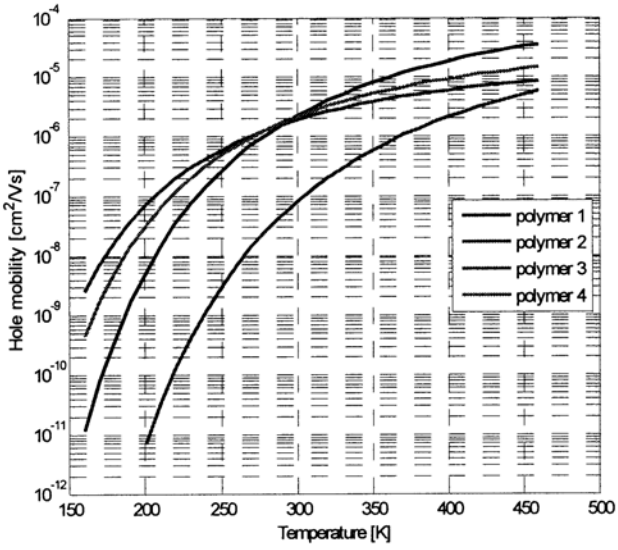

Figure 3. Carrier mobility versus temperature without an applied electric field

$$\mu(T,E,N_t) = \mu_0 \left(\frac{N_s}{N_t}\right)^n \times \exp\left[\left(\frac{E}{E_c}\right)^{1/2} - \left(\frac{T_c}{T}\right)^2\right] \quad (5)$$

In Equation (5) N_s and N_t denote the concentrations of carriers and traps, while E_c and T_c are the critical electric field and the temperature. The proposed model is very simple and besides the mobility dependence on temperature and electric field, it takes into account the concentration of traps which causes carrier scattering [10].

RESULTS

According to the described model, results were obtained for various temperatures, electric fields and trap densities. The following input parameters for the considered four types of polymers, with structural formulas shown in Figure 1b, were used [11,12]:

$$\mu_0 = (0.28; 0.14; 0.03; 0.06) \cdot 10^{-3} \left[\frac{\text{cm}^2}{\text{Vs}}\right]$$

$$\sigma = (0.085; 0.106; 0.063; 0.071)\ [\text{eV}]$$

$$\Sigma = (0.7; 1.4; 1.5; 1.6)$$

$$T_c = (660; 820; 490; 550)\ [K]$$

$$N_s = 10^{21}\ [\text{cm}^{-3}];\ N_t = (10^{17} - 10^{19})\ [\text{cm}^{-3}]$$

$$n = (0.25 - 0.50);\ E_c = 4 \cdot 10^6 \left[\frac{\text{V}}{\text{cm}}\right].$$

The aim was to achieve good correspondence with the experimental results. The carrier mobility without an applied electric field is presented in Figure 3. Because of comparison with experimental data, slope β was calculated:

$$\beta = \partial \ln(\mu/\mu_0) / \partial E^{1/2} \quad (6)$$

The following figures (Figures 4–7) show the carrier mobility dependence on the applied electric field and temperature. The carrier mobility dependence on the traps concentration and carrier molecule concentration are also included.

DISCUSSION

As can be seen from the presented simulation results, very good agreement between the obtained and experimental data was achieved. At high temperatures, slope β approaches zero regardless of whether an electric field is applied or not. For very high electric fields Poole–Frenkel's dependence was proved. Two different models of carrier mobility were

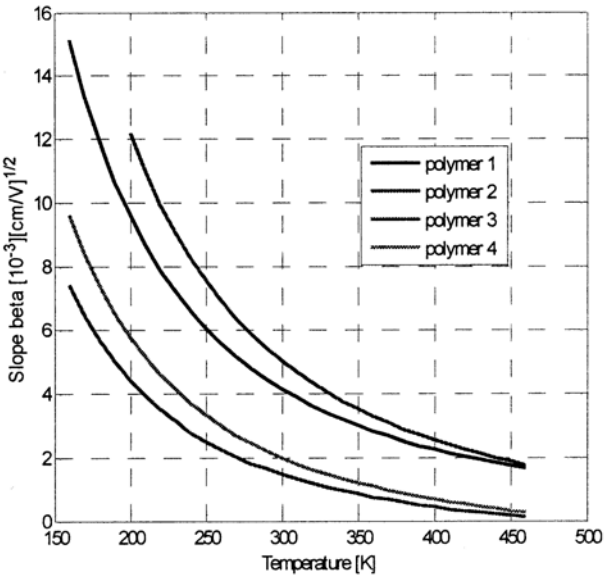

Figure 4. Slope β versus temperature with an applied electric field

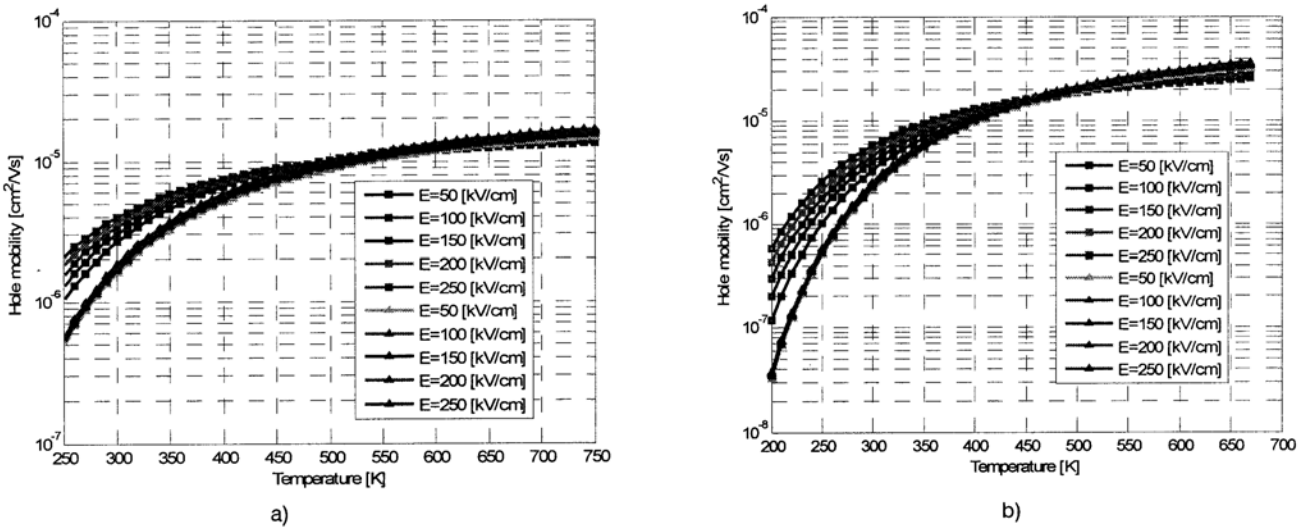

Figure 5. Carrier mobility versus temperature for different applied electric fields: a) polymer 3; b) polymer 4

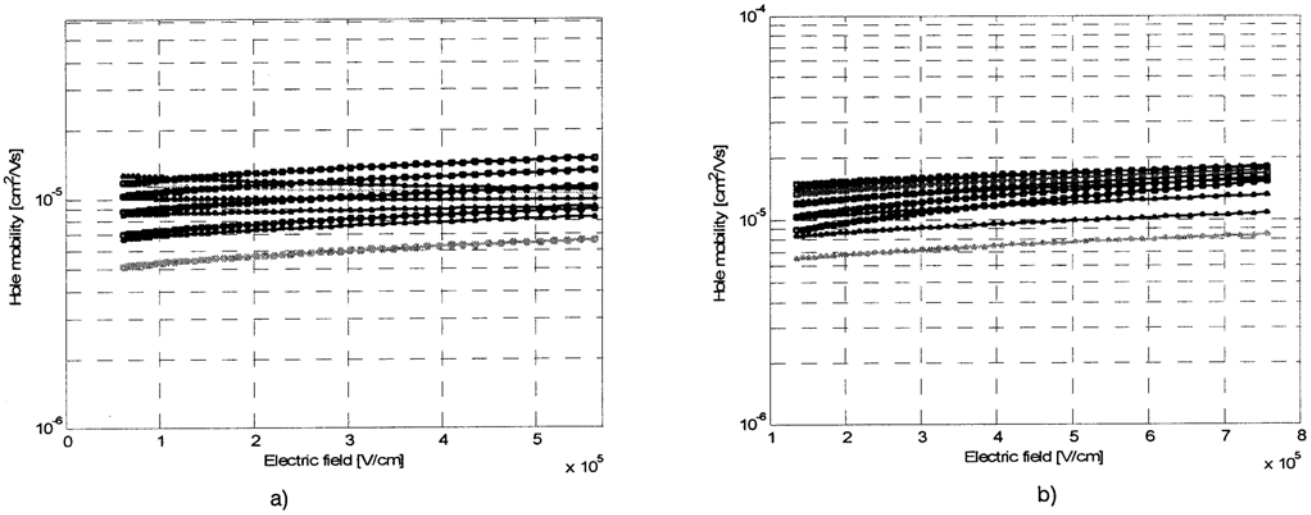

Figure 6. Carrier mobility versus electric field at different temperatures: a) polymer 3; b) polymer 4 The temperatures range between 400 and 600 K

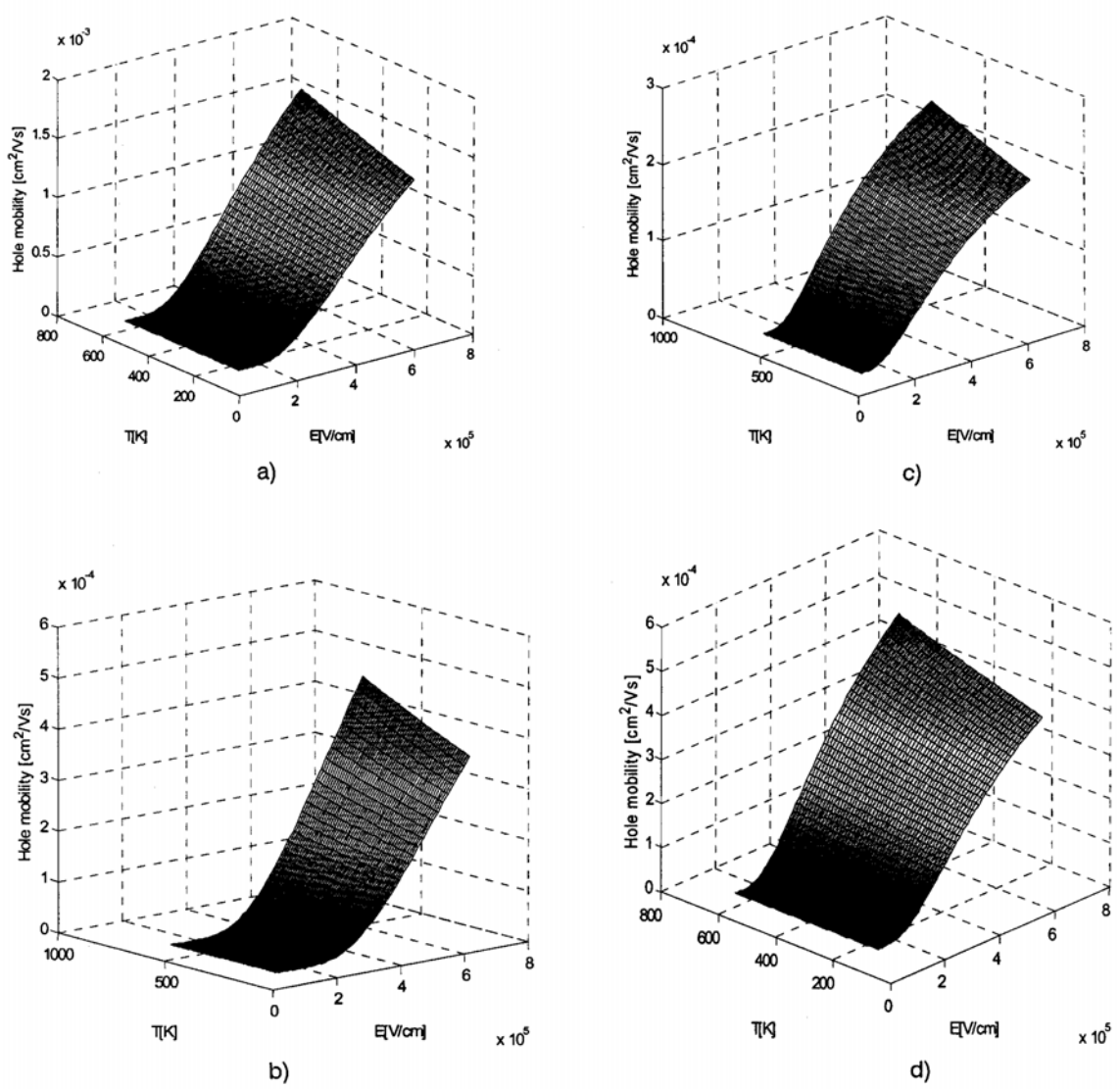

Figure 7. Carrier mobility dependence versus applied electric field, temperature and trap concentration ($N_t = 10^{17}$ cm^{-3}); (a) polymer 1; (b) polymer 2; (c) polymer 3; (d) polymer 4

compared in Figure 5 and excellent agreement was obtained. At very high temperatures with a constant applied electric field, the carrier mobility tends to a constant value. When constant temperature is assumed, the mobility dependence on electric field is linear (Figure 6). In comparison to the results obtained for different mobility models, very good agreement can be seen. As stated previously, the polymer layer structure has greatly influences the properties of the considered polymer device. The considered polymers have a zonal energetic spectrum with discrete energy levels inside the band gap. The mechanism of carrier transport is called phonon–activated hopping. This influence was taken into account through the trap density thus better matching with the known data was achieved.

CONCLUSION

The developed novel POFET carrier mobility model can be widely used, because it takes into account the main features of polymer–based semiconductor structures. Besides the fact that the model includes the mobility dependence on temperature and electric field, trap density effects are also described in the proposed model. The results obtained using the model are in good agreement with the experimentally obtained results. The model is comparatively simple, it can be easily applied. It is expected that the model can be efficiently used for further investigations as well as for simple calculation of the POFET current–voltage I (V) characteristics.

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IZVOD

ANALITIČKI MODEL POKRETLJIVOSTI NOSILACA U POLIMERNOM FET–U

(Naučni rad)

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U radu je, na osnovu modela i eksperimentalnih rezultata dostupnih iz literature, za pokretljivost nosilaca naelektrisanja u polimernim materijalima, predložen analitički model za pokretljivost nosilaca u kanalu POFET–a (Polymer Field Effect Transistor). Predloženi model je univerzalan, jer sadrži temperatursku zavisnost pokretljivosti, zavisnost od električnog polja i od koncentracije centara zahvatanja (zamki) u kanalu POFET–a. Uz to, model je relativno prost i lako primenljiv, a daje zadovoljavajuće rezultate. Na osnovu prezentovanog modela izvršena je simulacija pokretljivosti u funkciji relevantnih parametara i rezultati su prikazani grafički uporedo sa eksperimentalno dostupnim, odakle se vidi relativno dobro slaganje. Predloženi model za pokretljivost daje mogućnost jednostavnog proračuna strujno–naponske karakteristike ove vrste tranzistora.

Ključne reči: Model pokretljivosti nosioca • Polimerni tranzistor • Električne karakteristike • Simulacija

Key words: Carrier mobility model • Polymer Transistor • Electrical characteristics • Simulation