Investigation of Inertness of Photodischarge of Two-Layer Organic Photoreceptors

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This article presents the experimental photodischarge kinetics and the theoretical investigations of a two-layer organic semiconductor photoreceptor construction that consists of a charge photogeneration layer (CGL) and a hole transport layer (CTL). The experimental results and the theoretical calculations indicate that hole transport in the CTL is significantly influenced by the hole localization in different local energy levels and that these energy levels are at least partly induced by the electric field. The calculated hole localization level density is $(0.3 - 1.5) \times 10^{15}$ cm^{-3} and the initial hole lifetime relative to localization under the conditions of this investigated, is close to initial transit time T_0. The time of hole liberation from a localized state is close to 10^{-3} s, exceeding T_0 by several times, and therefore the hole localization in the CTL determines the inertness (potential discharge rate) of the photoreceptor.

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Introduction

The functional technical capabilities of electrophotographic copying devices and laser printers are mainly determined by the physical properties of photoreceptors. In recent years, photoreceptors are mostly manufactured from organic semiconductors, either in single-layer construction where the charge photogeneration and transport take place in the same layer or in a two-layer construction that consists of the charge transport layer (CTL) intermediate between the charge photogeneration layer (CGL) and the substrate for positive polarity photoreceptors or the layer construction can be inverted for negative polarity photoreceptors.[1,2] Organic photoreceptors that are used in high-speed copying devices and in laser printers are characterized by a sufficiently high initial charging potential ($U_0 \geq 700$ to 800 V), high photosensitivity (as high as 150 to 200 m^2/J in the wavelength region 700 to 800 nm), low residual potential voltage, and high photodischarge rate. The time required to discharge completely a photoreceptor exposed to a short pulse of light should not exceed the time interval between laser exposure and toner development. Otherwise, the electrostatic contrast voltage would be less than the maximum achievable contrast level and produce an image with a low toner density. In the case of short-pulse exposure, the minimum photodischarge time is determined by the charge carrier drift mobility (usually hole mobility) and its dependence on electric field strength.

In the dual layer constructions, these organic photoreceptor properties are determined by the physical phenomena that take place within the CGL and CTL. Therefore, an understanding of the physical phenomena is important for the effective control of these properties. A large number of publications[1–3] address the topic of charge carrier transport in organic semiconductors. Experimental and theoretical investigations dealing with hole transport under small-charge drift conditions describe a significant dependence of the hole mobility on electric field strength. Additional publications describe the influence of polymeric binder material on hole localization[4] and mobility and the dispersive transport of charge carriers under long exposure conditions when the carrier photogeneration is instantaneous and occurs at the layer surface.[5] In the case of a two-layer photoreceptor exposed to a sufficiently large dose of photons, hole injection from the CGL into the CTL is not instantaneous and the hole transport can not be described by small-charge drift model. The discharge kinetics of photogenerated carriers under these conditions have not been adequately investigated and explained. The purpose of this inves-

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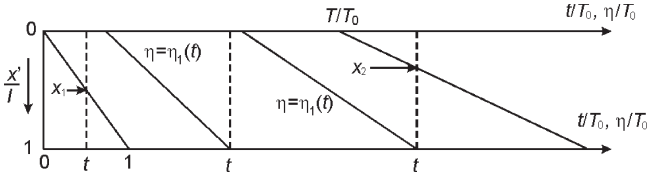

Figure 1. Hole trajectories in the CTL and integration regions in the case $[u(1–p)]^{1} < 1$.

tigation is to provide a theoretical explanation for the dependence of hole mobility on the electric field strength and the hole localization in the CTL and compare these predicted values to the experimental photodischarge kinetics of two-layer photoreceptors.

The Model of Charge Transport in a Two-Layer System

The bias voltage, potential decay kinetics of a two layer organic photoreceptor (OPR) is predominately determined by three factors: the charge carrier photogeneration and its transport in the charge (photo)generation layer (CGL), the transport of the injected holes from the CGL into the charge transport layer (CTL), and hole transport through the CTL. The description of these phenomena will be based on the assumptions that hole migration through the OPR system occurs only in the z-direction and that photogeneration of the holes-electrons is instantaneous. The transport time variable, t, will be measured from the moment of photogeneration (from the end of exposure) and a positive polarity, two layer construction where the CGL is above the CTL will be considered—an analogous explanation exists for the negative polarity, two layer construction. The OPR potential kinetics $U(t)$ will be calculated neglecting the small decrease in surface potential due to the CGL since the decrease of the CGL potential is a small fraction of the total potential decrease through the OPR system. Such an approach simplifies the description regarding the role of electrons created in the CGL.

By assuming that light absorption in the CGL is homogeneous, the initial densities of the photogenerated electrons and holes do not depend on their generation site. In addition, it will be assumed that the charge carriers drift freely in the electric field, and all holes are freely transported into the CTL after reaching the CGL-CTL interface. Hole displacement during an infinitesimal time interval, dt, is equal to

$$\mathrm{d}x = \mu_g E_g \mathrm{d}t \tag{1}$$

The coordinate x is measured from the exposed surface of the CGL, μ_g is the hole mobility in the CGL and is assumed constant, and E_g is the electric field strength in the photogeneration layer. Under electrographic mode conditions (open circuit), in each region where there is no electron transport the hole current density j and electric field strength E are related to each other by the equality

$$j + \varepsilon_0 \varepsilon \frac{\partial E}{\partial t} = 0, \tag{2}$$

where ε is dielectric constant and ε_0 is the permittivity constant. It is sufficient to know the E_g value at the CGL interface that is in contact with the CTL in order to characterize hole injection into the CTL. This value is determined by considering that all of the electrons reach the exposed surface of the CGL during photogeneration. This assumption means that the electric field strength in the CGL and the rate of hole injection into the CTL are under-estimated to a certain extent. This fact should be taken into account when interpreting the calculated results. Thus, the Poisson equation describing E_g is now the following:

$$\frac{\partial E_g}{\partial x} = \frac{\mathrm{e}}{\varepsilon_0 \varepsilon_g} p_g, \tag{3}$$

where p_g is hole density, e is the elementary charge, ε_g is the dielectric constant of the CGL. Drift current density is

$$j = e\mu_g p_g E_g. \tag{4}$$

Using Eqs. (2) and (4) to eliminate p_g, Eq. (3) becomes

$$\frac{\partial E_g}{\partial x} + \frac{1}{\mu_g E_g}\frac{\partial E_g}{\partial t} = 0 \quad . \tag{5}$$

Equation (5) is solved by the method of characteristics, that is, along curvilinear coordinates defined by Eq. (1).[6] After expressing $\mu_g E_g$ from Eq. (1) and substituting into Eq. (5), the left hand side of Eq. (5) becomes a complete derivative of E_g relative to x:

$$\frac{\mathrm{d}E_g}{\mathrm{d}x} = 0. \tag{6}$$

Thus, the electric field strength E_g does not depend on x, so that the solution of Eq. (6) can be expressed as follows:

$$E_g(x, x_0) = E_g(x_0) = (1-p)E_0 + \frac{em}{\varepsilon_0 \varepsilon_g} x_0, \tag{7}$$

where E_0 is electric field strength in the photogeneration layer before its exposure; the p parameter reflects the above mentioned decrease of initial electric field strength caused by photogenerated electrons and is generally expressed as the ratio between the total charge of all holes that were injected into the CTL and the charge deposited on the CGL surface during charging; m is hole density; x_0 is the initial coordinate of a given hole front. Substitution of Eq. (7) into Eq. (1) and integration (taking into account that $x = x_0$ when $t = 0$) gives

$$t = \frac{x - x_0}{\mu_g E_g(x_0)}. \tag{8}$$

By expressing x_0 from Eq. (8) and substituting it into Eq. (7), we obtain an expression for E_g as a function of time t. The value of E_g on the CGL substrate is obtained by substitution, $x = l_g$, where l_g is the CGL thickness. This value is

$$E_g(t) = (1-p)E_0 + \frac{em}{\varepsilon_0 \varepsilon_g}\left(l_g - (1-p)\mu_g t E_0\right)\cdot\left(1 + \frac{em\mu_g t}{\varepsilon_0 \varepsilon_g}\right)^{-1}. \tag{9}$$

This formula is valid for all times t that satisfy the condition $t \le T = l_g/(\mu_g(1-p)\,E_0)$, where T is the time when the trailing edge of holes ($x_0 = 0$) reaches the CGL-CTL interface ($x = l_g$).

The transport of holes that are injected into the CTL is analyzed by an approximation based on the assumption that hole transport is the result of unhindered drift through the layer. In such a case, Eqs. (1), (2) and (5) are still valid after replacing CGL parameters by their CTL counterparts, and the CTL parameters will be denoted without subscripts, that is, the CTL dielectric constant will be denoted as ε, and so on. Now the holes appear at the same location but at different moments in time, and the left hand side of Eq. (5) is expressed as a complete time derivative. Thus, the equations for the electric field strength and hole characteristics in the CTL are the following:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = 0 \quad , \quad \mathrm{d}x = \mu E \mathrm{d}t \tag{10}$$

and their solutions are

$$E(t,\eta) = E(\eta),\ x = \mu E(\eta)(t-\eta)\,. \tag{11}$$

Here, $E(\eta)$ is the electric field strength at a time $t = \eta$ at the CTL surface that is in contact with the CGL. This electric field strength is given by the equality

$$E(\eta) = \frac{\varepsilon_g}{\varepsilon} E_g(\eta)\,, \tag{12}$$

where $E_g(\eta)$ is expressed by the Eq. (9) after replacing t by η. Hole mobility μ, which appears in the second Eq. (11), depends on electric field strength. Based on experimental results (presented later in this article), the hole mobility is expressed as follows:

$$\mu = \mu(\eta) = \mu_0 \exp\left(\alpha_0 \sqrt{E(\eta)}\right), \tag{13}$$

where μ_0 and α_0 are experimentally determined constant values. Equalities of Eq. (11) will be expressed in dimensionless quantities. Time variables t and η are expressed in units of

$$T_0 = \frac{l}{\mu_0 \exp\left(\alpha_0 \sqrt{E(\eta=0)}\right) E(\eta=0)}\,, \tag{14}$$

which is the duration of hole transit through the CTL at the initial electric field strength. Coordinate x will be expressed in units of the CTL thickness l. Denoting the OPR charging potential as U_0 and using it to express the initial electric field strengths $E_g(\eta = 0)$ and $E(\eta = 0)$, the ratio between the duration T of hole injection into the CTL and hole transit duration T_0 can be expressed as follows:

$$\frac{T}{T_0} = \frac{1}{u(1-p)}\,. \tag{15}$$

In this equality

$$u = \frac{l\varepsilon\mu_g}{l_g\varepsilon_g\mu_0 e^{\alpha}} \text{ and } \alpha = \alpha_0\sqrt{\frac{U_0}{l(1+\varepsilon\varepsilon_g^{-1}l_g l^{-1})}}\,.$$

Under the conditions formulated above, two cases should be distinguished when calculating OPR potential kinetics $U(t)$: $T \ge T_0$, or $u(1-p) \le 1$, and $T < T_0$, or $u(1-p) > 1$. Since

$$U(t) = \int_0^l E(x,t)\mathrm{d}x\,, \tag{16}$$

whereas the electric field strength is defined on hole trajectories (characteristics of Eq. (11)), the integral of Eq. (16), will be calculated by partitioning the integration region and transforming the integration variable. The diagram of hole trajectories and integration regions is shown in Fig. 1. The following relations are found:

1. In the situation where $u(1-p) \le 1$:
a) the time interval $0 \le t \le 1$

$$\frac{U(t)}{U^*} = 1 - t + \int_0^t F(\eta,t)\mathrm{d}\eta\,, \tag{17}$$

where $U^* = \varepsilon_g\varepsilon^{-1}lE_0$,

$$F(\eta,t) = e^{\alpha(\sqrt{E^*(\eta)}-1)}\left(1+\frac{up(t-\eta)}{1+up\eta}\left(1+\frac{\alpha}{2(1+up\eta)^{1/2}}\right)\right)(1+up\eta)^{-2}, \tag{18}$$

$$E^*(\eta) = (1+up\eta)^{-1};$$

b) the time interval $1 < t \le [u(1-p)]^{-1}$

$$\frac{U(t)}{U^*} = \int_{\eta_1(t)}^t F(\eta,t)\mathrm{d}\eta\,, \tag{19}$$

where $\eta_1(t)$ is found from the equation

$$E^*(\eta_1)(t-\eta_1)e^{\alpha\left(\sqrt{E^*(\eta_1)}-1\right)} = 1 \tag{20}$$

($\eta_1(t)$ is the time when hole entered the CTL, given the time t when they reach the layer substrate).

c) the time interval $[u(1-p)]^{-1} < t \le t_0$

$$\frac{U(t)}{U^*} = (1-p)^2 e^{\alpha\left(\sqrt{1-p}-1\right)}\left(t-\frac{1}{u(1-p)}\right) + \int_{\eta_1(t)}^{(u(1-p))^{-1}} F(\eta,t)\mathrm{d}\eta\,, \tag{21}$$

where

$$t_0 = (1-p)^{-1}\left(u^{-1} + e^{-\alpha\left(\sqrt{1-p}-1\right)}\right) \tag{22}$$

is the time during which the trailing hole front reaches the CTL substrate;

d) when $t > t_0$, $U(t) = U(t_0)$.

2. In the situation where $u(1-p) > 1$:
   a) the time interval $0 \le t \le [u(1-p)]^{-1}$, potential $U(t)$ is expressed by Eq. (17);
   b) the time interval $[u(1-p)]^{-1} < t \le 1$

$$\frac{U(t)}{U^*} = 1 - t + (1-p)^2\left(t - \frac{1}{u(1-p)}\right)e^{\alpha\left(\sqrt{1-p}-1\right)} + \int_0^{(u(1-p))^{-1}} F(\eta,t)\,\mathrm{d}\eta \quad ; \qquad (23)$$

   c) the time interval $1 < t = t_0$, potential $U(t)$ is expressed by Eq. (21);
   d) when $t > t_0$, $U(t) = U(t_0)$.

Detailed derivation of Eqs. (17) – (23) are in Appendices 1 and 2, available as Supplemental Material on the IS&T website.

Results of calculations according to Eqs. (17) through (23) are presented in Fig. 7. The free hole drift model in the CTL predicts a faster decrease of potential voltage (curves 5, 6) than that observed experimentally. A more accurate description of the role of electrons created in the CGL would lead to an even more abrupt decrease of potential. It follows that hole transport in the CTL cannot be described only as their free drift. Since there are no electrons in the CTL, the slowdown of hole transport could be caused by hole localization in local levels. An additional model is presented based on the assumption that holes are trapped in the CTL into localized states from which they can be thermally liberated.

The hole localization level density will be denoted as M and it will be assumed to be independent of x. The density of localized holes will be denoted as m and will be assumed to be equal to 0 at the initial moment of time ($t = 0$).

Time dependence of m is described by Eq. (24)

$$\frac{\partial m}{\partial t} = \gamma M p_t\left(1 - \frac{m}{M}\right) - \beta m\,, \qquad (24)$$

where γM is probability of hole localization at time $t = 0$; β is probability of hole liberation from a localized state (this probability is assumed to be constant); and p_t is density of free holes in the CTL (Eq. (24)) analysis is given in the Appendix. By applying Eqs. (2) and (4) to the CTL, the hole density p_t is expressed in terms of electric field strength:

$$p_t = -\frac{\varepsilon_0\varepsilon}{e\mu E}\frac{\partial E}{\partial t}\,. \qquad (25)$$

After substituting this expression into Eq. (24) and taking into account the relation $\varepsilon_0\varepsilon\gamma/e\mu = 1$, which is usually applied when solving similar problems, the integration of Eq. (24) with respect to the time variable gives

$$m(x,t) = M\cdot\left(1 - E(x,t)\cdot e^{-s\cdot t}\cdot\left(1 + s\cdot\int_0^t \frac{e^{s\cdot t'}}{E(x,t')}\,\mathrm{d}t'\right)\right), \qquad (26)$$

where $s = \beta T_0$, and T_0 is expressed by the equality in Eq. (14). In Eq. (26), time variables t and t' are expressed in units of T_0 and the electric field strength $E(x,t)$ is expressed in units of the initial field strength in the CTL, E_{0t}. Thus, all of the quantities in parentheses on the right-hand side of Eq. (26) are dimensionless.

The Poisson equation, which describes electric field strength, will now take into account not only the charge of free holes, but also the charge of localized holes. This Poisson equation, written in dimensional quantities, is the following:

$$\frac{\partial E(x,t)}{\partial x} = \frac{e}{\varepsilon_0\varepsilon}(p_t + m)\,. \qquad (27)$$

Using Eqs. (25) and (26) and expressing field strength in units of its initial value E_{0t}, we can rewrite Eq. (27) in dimensionless variables:

$$\frac{\partial E(x,t)}{\partial x} + R(x,t)E(x,t) = Q(x,t)\,, \qquad (28)$$

where

$$R(x,t) = ae^{-s\cdot t}\left(1 + s\cdot\int_0^t \frac{e^{s\cdot t'}}{E(x,t')}\,\mathrm{d}t'\right),$$

$$Q(x,t) = a - \frac{1}{\mu E(x,t)}\frac{\partial E(x,t)}{\partial t}\,, \qquad (29)$$

$$a = \frac{\mathrm{e}Ml}{\varepsilon_0\varepsilon E_{0t}}\,, \quad \mu = e^{\alpha\left(\sqrt{E(x,t)}-1\right)}. \qquad (30)$$

Here, a and E_{0t} are assumed to be independent of x, therefore the initial value of the solution of Eq. (28) is $E(x,0) = 1$. The boundary condition of the solution of Eq. (28) is the following:

$$E\,(0,t) = (1 + upt)]^{-1} \text{ when } t \le [u(1-p)]^{-1},$$

$$E(0,t) = 1 - p \text{ when } t > [u(1-p)]^{-1}. \qquad (31)$$

The field strength in Eq. (28) has been solved numerically.

If a dielectric barrier exists between the CTL and substrate that completely prevents the passage of holes when electric field strength is below a certain threshold value, then the time dependence of the system potential $U(t)$ is given by the equation

$$\frac{U(t)}{U_0} = \frac{U_t(t)}{1+k} + \frac{k}{1+k}\,, \qquad (32)$$

where

$$U_t(t) = \int_0^1 E(x,t)\mathrm{d}x\,, \quad k = \frac{\varepsilon\cdot l_b}{\varepsilon_b\cdot l}\,. \qquad (33)$$

Here, l_b is the barrier layer thickness, ε_b is its dielectric constant, and $E(x,t)$ is the solution of Eq. (28). In the previously discussed case of free hole drift in the CTL, the function $U_t(t)$ in Eq. (32) is given by Eqs. (17) to (23).

Results and Discussion

The theoretically calculated photodischarge inertness was compared with the results obtained from experi-

mental measurements. These values were used to evaluate the localization level density and to determine the time of hole liberation. The hole drift mobility was measured, its dependence on electric field strength was determined, and the photoreceptor discharge kinetics, under exposure to a short pulse of light, was determined.

Experimental Details

This investigation focused on a two-layer organic photoreceptor construction that consists of (coating sequence) an aluminized polyester film substrate, a 0.2 – 0.3 μm thick dielectric charge injection barrier layer, a 11 μm thick hole transport layer consisting of a commercial hydrazone[7] CTM (Fig. 2) and polycarbonate (PC Z) (1:1 w/w), and a 0.5 μm thick CGL formed of titanyl phthalocyanine (TiOPc) with polyvinylbutyral (PVB) binding material (7:3 w/w) coated on the CTL surface. This photoreceptor is referred to as OPR 1. Hole drift mobility in this photoreceptor was measured using the time-of-flight (TOF) method[8] in electrophotographic mode.[9]

The photoreceptor was charged positively or negatively up to the desired initial potential (U_0) using a scorotron-type charger and then exposed to a short (~10^{-6} s) low-intensity pulse of strongly absorbed light at 780 nm. The time constant of the measurement circuit was appropriately chosen so that the measured signal was proportional to the rate of potential variation (dU/dt) and the small-charge drift current kinetics were measured (Fig. 3). The charge carriers that were photogenerated in the CGL by a short pulse of light were separated by the electric field and the holes drift through the CTL towards the OPR substrate. When the leading edge of the hole packet reached the substrate electrode, a break appeared on the small-charge current kinetics. This break was used to determine the hole transit time (tt) through the CTL (Fig. 3).

The curves (dU/dt) = $f(t)$ have been plotted on the double-logarithmic scale (Fig. 3, curves 1 to 8) to increase accuracy for determining the hole transit time. The hole drift mobility was calculated from the formula $\mu = l^2/U_0 \cdot t_t$, where t_t was a measured value. For example, at an electric field strength of 3.6×10^5 V/cm the mobility is equal to $\mu = 1.1 \times 10^{-6}$ cm^2/V·s in OPR-1. Hole drift mobility in OPR 1 depends on electric field strength E and is described by the exponential dependence, $\mu = \mu_0 \exp\left(\alpha\sqrt{E}\right)$ (Fig. 4), where $\alpha = 0.0048$ (cm/V)$^{0.5}$, and the hole mobility extrapolated to a zero field is $\mu_0 = 6.2 \times 10^{-8}$ cm^2/V·s.

The photoreceptor photodischarge inertness was measured using equipment with a sufficiently high input resistance to ensured the voltage mode, so that the registered signal is proportional to potential decrease with time: $V_{signal}(t) \sim \Delta U(t)$. The OPR was positively charged to the desired potential and exposed to a short pulse of light with a wavelength 780 nm whose light pulse energy was determined using a IL 1700 Research Radiometer.

Calculated and Experimental Photodischarge Kinetics

Figure 5 presents photodischarge curves of an OPR 1 photoreceptor, which was positively charged to various potential magnitudes, then exposed to a short (10^{-6} s) light pulses with an energy 11 erg/cm^2. Figure 6 presents photodischarge curves when the photoreceptor was charged to a constant potential of 795 ± 5 V and exposed to a 10^{-6} s-long pulse of 780 nm light with various intensities. The initial photodischarge rate

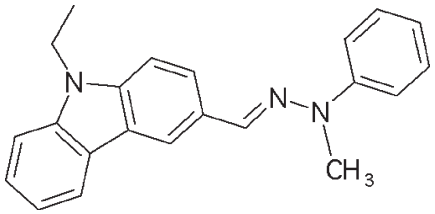

Figure 2. The structural formula of the hydrazone.[9]

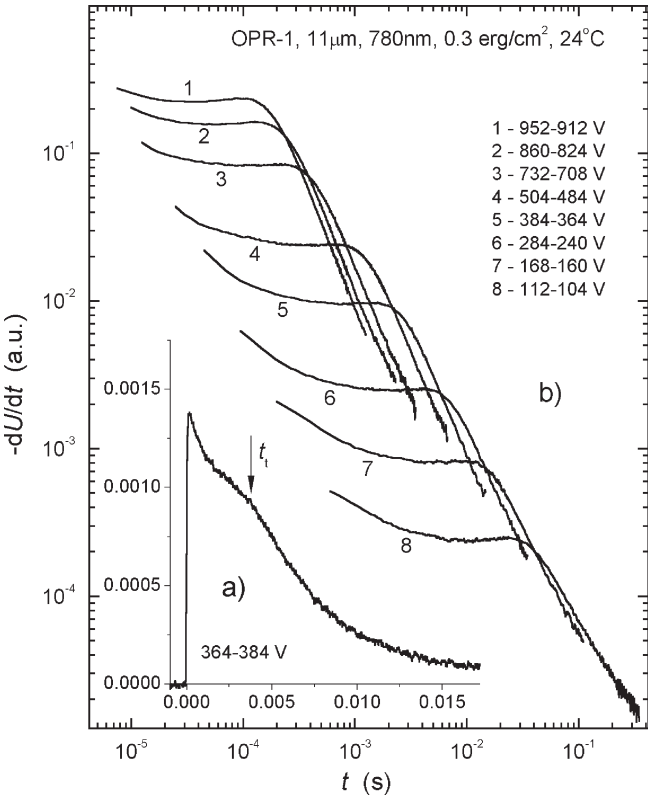

Figure 3. Kinetics of hole small charge drift current in the OPR 1 in linear scale (a) and double logarithmic scale (b).

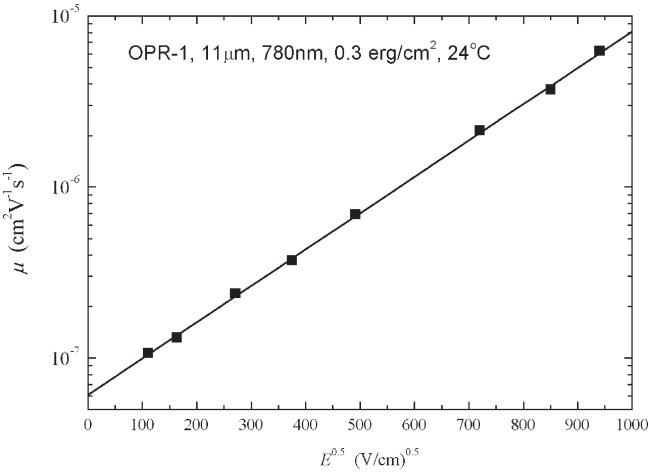

Figure 4. Dependence of hole drift mobility in the OPR 1 on electric field strength.

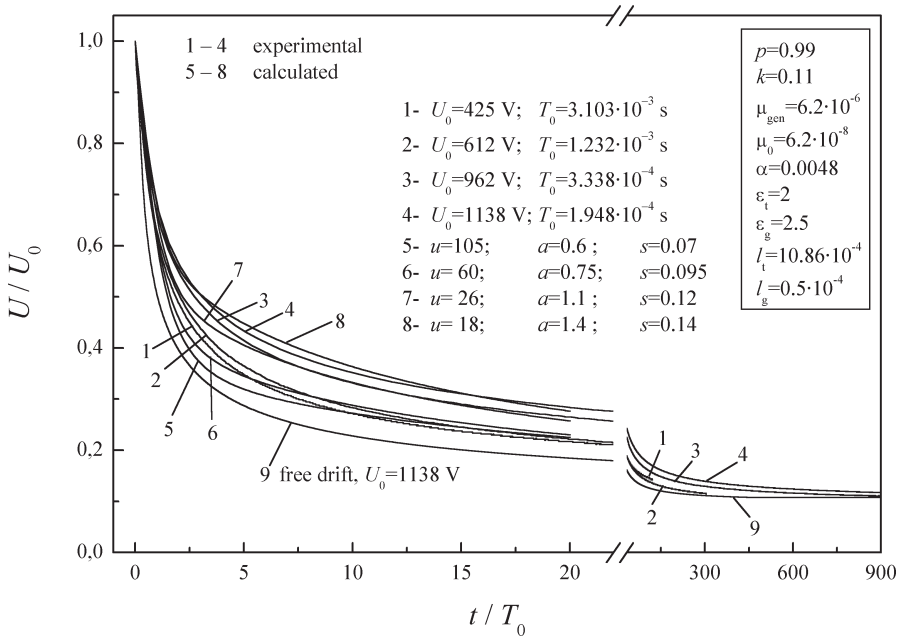

Figure 5. Photodischarge curves of OPR 1, charged to different initial potentials, under exposure to light pulses with energy 11 erg/cm^2, duration 10^{-6} s and wavelength 780 nm. Curves 5 – 8 correspond to theoretical calculations taking into account hole localization in local levels.

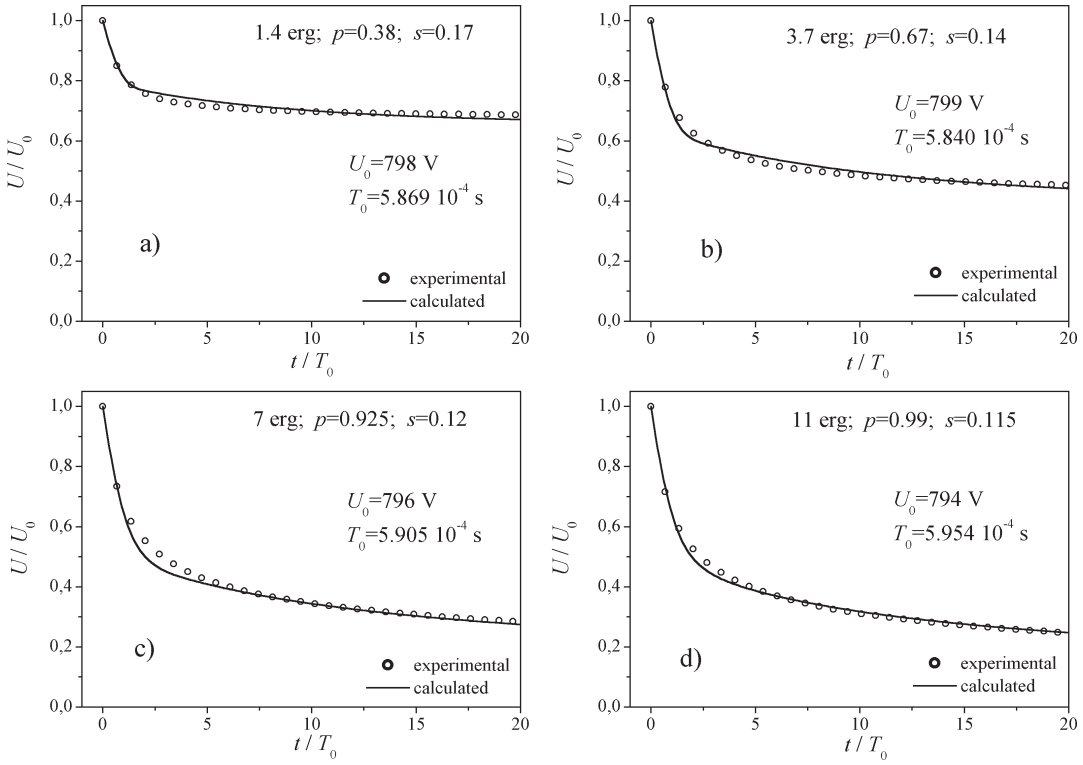

Figure 6. Photodischarge curves of OPR 1, charged to the same potential, under exposure to short (10^{-6} s) pulses of 780 nm light with different energies. Theoretical calculations have been done taking into account hole localization in local levels. For all curves u = 37, a = 1, k = 0.11.

decreased significantly as the initial charging potential decreased because of the dependence of the hole drift velocity on the electric field strength. Figure 7 illustrates that an 11 erg/cm^2 light energy density is sufficient to discharge the OPR 1 photoreceptor practically to the residual potential.

Figure 7 presents the calculated photoreceptor photodischarge kinetics for the case of free hole drift and compares them with the corresponding experimental results. In this case, the theoretical model predicts a faster potential decrease than that observed experimentally, despite the fact that the model underestimates

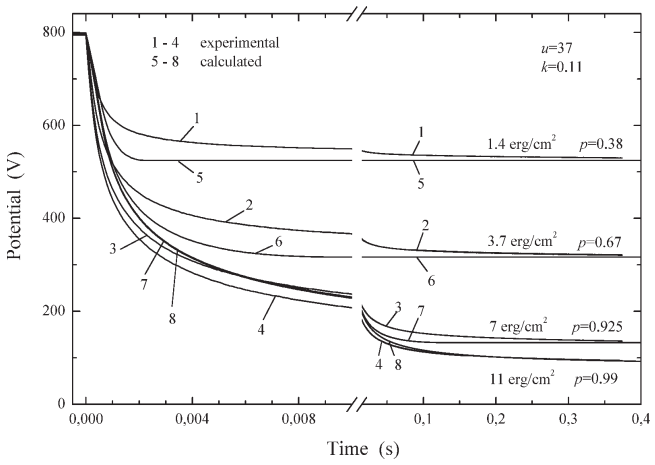

Figure 7. Photodischarge curves of OPR 1, charged to the same initial potential, under exposure to short pulses of light with different energies. Curves 5 – 8 correspond to theoretical calculations, neglecting hole localization in local levels (free drift with field-dependent mobility).

the rate of hole injection into the CTL, as mentioned previously. This could be a result of hole localization in local levels in the CTL.

Figures 5 and 6 compare the calculated results obtained by using Eq. (28) and taking hole localization into account with the experimental data. This comparison shows that the theoretical model of hole localization in the OPR 1 is in good agreement with the experiment.

The model parameter p, which gives the relative number of injected holes, cannot be evaluated directly from the experiment. In all cases, its value has been determined from the requirement that the theoretically calculated asymptotical value of $U(t)$, which is equal to $1 - p/(1 + k)$, coincides with the empirical value (here, k is the barrier parameter in Eq. (33), and $U_t(\times) = 1 - p$). Values of parameters a and s have been found from the requirement of optimal agreement between calculation results and experimental data: a – in the region of fast potential decrease (over a period of several T_0), s – in the region of transition to the slow decrease ($t = (10 - 20) \cdot T_0$).

If values of M were constant, then according to Eq. (30), parameter a would be inversely proportional to charging potential U_0. However, values of M calculated from the determined values of a (Fig. 5) are the following: $M = 1.5 \times 10^{15}$ cm^{-3} when $U_0 = 1138$ V; $M = 0.24 \times 10^{15}$ cm^{-3} when $U_0 = 425$ V. This indicates that hole localization levels are at least partly induced by electric field. It can be supposed that this can occur when charges of organic molecules are polarized by external electric field thus forming potential wells of adequate width and depth in which charge carriers (holes in our case) hopping through doping molecule states will be localized. Another possible cause of formation of localization states should be the change of orientation of doping molecules or their fragments under influence of electric field. Such localization states of course are temporary and when electric field is sufficiently decreased they disappear. Consequently field induced states cannot cause space charge buildup and increase of residual potential during repeated xerographic cycling, because electric field is week at the end of photodisharge.

Apparently field induced states should not modify charge carrier mobility measured using the small signal method, because electric field is constant during testing. When this field is strong enough for formation of induced states such sites do not change and localized charge carriers should remain on them. More detailed theoretical investigation of induced states should be based on the modified Eq. (24) but this is a separate problem. The simplified model in which density of localizing states M is considered constant is used in this investigation and it enables us to state only that such states exist.

We assumed that $\gamma = e\mu/\varepsilon_0\varepsilon$; the time of localization in the initial field is then equal to $(\gamma M)^{-1} = T_0/a$. In the case of Fig. 5, this time is 5.3×10^{-3} s when $U_0 = 425$ V, and 1.5×10^{-4} s when $U_0 = 1138$ V, that is, close to T_0. The shape of dependence of the liberation parameter β on electric field strength is most easily deduced from results presented in Fig. 6, when hole liberation takes place at different values of electric field strength (depending on exposure intensity). According to results of Figure 6, the liberation time $t = 1/\beta = T_0$/s is equal to $(6 - 9)\ T_0$ and it insignificantly increases with exposure intensity from 4×10^{-3} s (1.4 erg) to 6×10^{-3} s (11 erg). Since the electric field strength in that intensity range varies about 3 fold, we can conclude that the liberation time is not significantly field dependent. Since the liberation time exceeds hole transit time T_0 by several fold, the hole localization in the CTL limits discharge rate of this photoreceptor.

Conclusions

1. The theoretical model of free hole drift with field dependent mobility predicts a faster decrease of photoreceptor potential than observed experimentally. The model of hole localization in the CTL is in better agreement with experimental data.
2. Hole localization levels in the investigated OPR are at least partially induced by electric field and their density is $(0.3 - 1.5) \times 10^{15}$ cm^{-3}, which corresponds to lifetime of $(5.3 - 0.2) \times 10^{-3}$ s relative to localization. This lifetime is close to hole transit time T_0.
3. The time of liberation from localized states is of the order of several T_0, therefore hole localization can limit the CTL discharge rate.

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