Depletion Charging and Surface Charge Injection in High Gamma Photoreceptors

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Abstract

In a single-layer organic photoconductor, depletion charging and surface charge injection are important issues in the electrophotographic process. During the initial stages of the charging process, a finite amount of free and shallow trap generated charges are swept out of the bulk of the photoconductive layer. Also, surface charges from corona ions can be injected into the layer due to the adsorption of corona generated chemicals on the free surface. Such depletion charging and surface charge injection reduce the charge acceptance. In single-layer high gamma photoreceptors, the charge acceptance is not reduced in any degree in spite of abundant depletable carriers and excess surface charge injection. The photoinduced and dark discharge characteristics of such high gamma photoreceptors are found to be well described by a mathematical structural trap model which takes into account both carrier depletion and surface charge injection.

Introduction

An electrophotographic single-layer high gamma organic photoreceptor typically consists of x-type metal-free phthalocyanine pigment dispersed in an insulating binder polymer. The photoreceptor receives a positive surface charge and is exposed to light absorbed by pigment. On exposure the surface potential decreases rapidly only after a threshold exposure. Weigl has referred to this as the induction effect [1]. We have clarified that the induction effect is due to “an intermediate trapping by structural units and kinetically induced process” [2]. We have found that structural traps give rise to the induction effect and this characteristic enables the fabrication of high gamma photoreceptors with good charge acceptance, low dark decay rate, high gamma, and fast photoresponse. In a single-layer organic photoreceptor, depletion charging [3] and surface charge injection [4] are important issues in the electrophotographic process. It has been pointed out that such depletion charging and surface charge injection reduce the charge acceptance. For the high gamma photoreceptors described in this paper we show that the charge acceptance is not reduced to any degree in spite of abundant depletable carriers and excess surface charge injection and we describe a mechanism to account for these observations. However, the characteristics of the induction exposure do depend on surface charge injection. An overcoat is effective in protecting the high gamma photoreceptor surface from carrier injection due to corona generated chemicals from corona chargers.

Experimental

A high gamma photoreceptor with x-type metal-free phthalocyanine pigment (15.5 vol%, the average diameter: 0.7 μm) dispersed in a polyester binder (*Digital Photoreceptor HGPC*) was invesitgated.

The charge acceptance, photoinduced and dark discharege characteristics were measured by conventional methods. The photoconductive durm was sequentially corona charged, exposed to monochromaitc light (710 nm), and then erased (tungsten lamp $\lambda > 640$ nm, 150 μJ/cm^2). The surface potential was measured 0.3 sec after the exposure. With each drum rotation the supply voltage to the light source was changed stepwise to obtain the photoinduced discharge characteristic of the photoreceptor. The diameter of the photoconductive drum was 80 mm and the circumferential velocity 55.85 mm/s giving an exposure time of 3.6 ms. The dark discharge was measured after corona charging by turning off the exposing light and stopping the drum roation.

Results

The surface potential was measured as a funtion the corona charge delivered for photoreceptor thicknesses of 10 μm, 18 μm, and 34 μm. The surface potential divided by the layer thickness are plotted as a function of the surface charge density in Figure 1. The solid curve was obtained by calculation from Equation (1), where the relative permittivity is taken to be 4.3. The corona charged surface potential V_c is defined as follows:

$$V_c = \frac{e\,Q_s\,L}{\varepsilon\,\varepsilon_0} \tag{1}$$

where e is the electronic unit of charge, L is the photoreceptor thickness, ε the relative permittivity, ε_0 the permittivity of vacuum, and Q_s the surface charge density in charges/cm^2.

The dark discharge characteristics for initial surface potentials of 400 V, 500 V, 700 V, and 900 V are shown in Figure 3. The photoinduced discharege characteristics for initial surface potentials of are shown in Figure 4.

Discussion

Phthalocyanine pigments dispersed in the high gamma photoreceptor form chains at pigment concentrations higher than about 20 wt% [5]. Figure 2 (a) gives a schematic view of formation of the pigment chain beneath the free surface. Under such circumstances, the contact point of a particle with an adjacent particle can be offset from base of the spherical bodies in the direction of the electric field. In this case free carriers are considered to be trapped within the saucer-shaped-space surrounded by insulating binder polymer. This is referred to as a structural trap. We call the depth a structural depth.

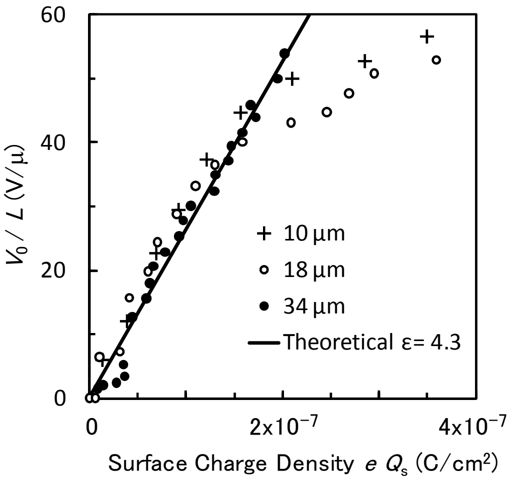

***Figure 1**. Surface potential V_0/thickness L vs. surface charge density e Q_s for Digital Photoreceptor HGPC of various thicknesses.*

Fig. 2(b) shows our structural trap model for theoretical calculations, where d_s is the structural trap depth and structural units are assumed to be distributed evenly in a photoconductive layer. We call one restricted carrier transport space with one structural trap a structural unit. The restricted carrier transport space corresponds to the bulk of the photoconductive particle and the upper end of d_s to the contact point to the next particle.

Borsenberger and Weiss have described a model due to Pai [6] to explain the charging characteristics of amorphous silicon photoreceptors. In this model it is assumed that a positively charged single-layer photoreceptor contains a uniform distribution of hole trapping centers (depletable center) that can be thermally ionized. The depletable centers are electrically neutral when occupied and negatively charged when ionized.

Fig. 2(a) shows depletion phenomenon for high gamma photoreceptors. Under the electric field due to corona charging, depletable holes are trapped in the structural traps. Negative depletable centers are distributed uniformly in all regions of the photoconductive particle. As for Fig. 2(a), one negative charge in a center of the particle represents uniformly distributed negative space charges. In Fig. 2(b), depletable holes are trapped in the structural traps and electron space charge is formed in all regions of the structural unit. As for Figure 2(b), one negative charge in a center of the unit represents uniformly distributed negative space charges.

Structural Traps and Surface Charge Injection

Weiss and Abkowitz have described that single-layer photoreceptors will be very sensitive to exposure to corona gases because the carrier generation material is exposued at the free surface [4]. All of the pigments and complexes used as carrier generation material will react with ozone, NO_x, and HNO_x, and the electrohotographic performance will be severely impacted [7]. Seino and Ebisu reported that exposure of a sigle-layer organic photoreceptor with CuPc to NO_x causes a rapid decrease in the charge acceptance [8]. Injection charges from the free surface are trapped by the first structural trap as shown in Fig. 2(a) and by the first structural trap shown in Fig. 2(b).

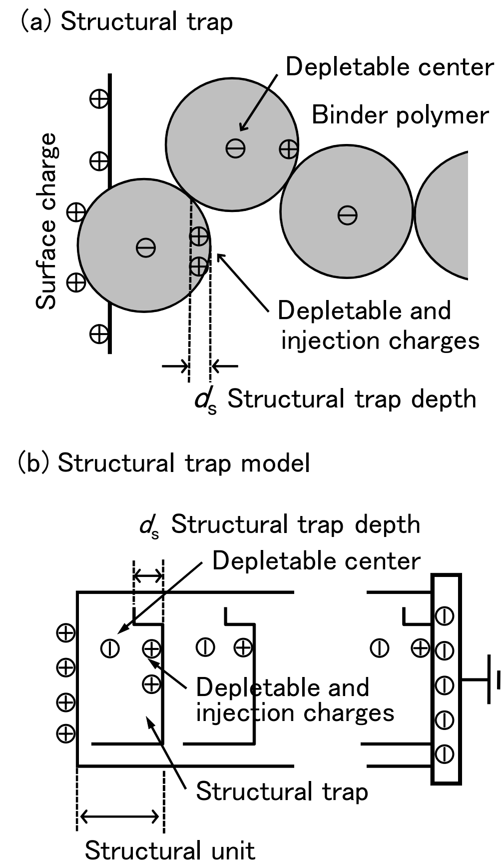

***Figure 2**. (a) A schematic view for structural traps produced by random contact between photoconductive particles dispersed in an insulating binder polymer. (b) A structural trap model with structural depth d_s for a high gamma photoreceptor.*

Charge Acceptance

The observable initial surface potential V_0 derived from the mathematical structural trap model is given by

$$V_0 = \frac{e\,L\,(Q_s - Q_{ij}/N_L - N_b L/2N_L)}{\varepsilon\,\varepsilon_0} \approx V_c \qquad (2)$$

where Q_{ij} is the injection charge density (charges/cm^2), N_b is the depletable center density (centers/cm^3), and N_L is the number of structural units in the photoconductive layer (> 10 units). In single-layer high gamma photoreceptors, the charge acceptance is not reduced in any degree in spite of depletable carriers and surface charge injection.

Photoinduced and Dark Discharge

With Fig. 2(b) as the initial condition, the thermal bulk carrier generation induces the dark discharge and the carrier photo-generation induces the photoinduced discharge. The theoretical curves for high gamma photoreceptors are calculated by a mathematical structural trap model [2] which takes into account both carrier depletion and surface charge injection.

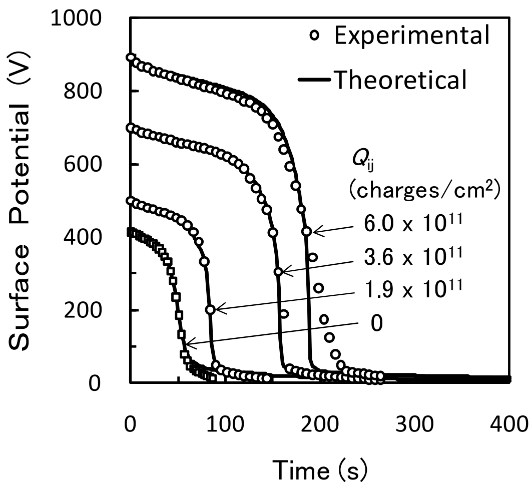

***Figure 3**. Dark discharge characteristics for Digital Photoreceptor HGPC. The photoreceptors were measured under conditions where the gasses from the corona were not vented. The theoretical curves are calculated with d_s= 0.02 μm, N_L = 15 units, N_b = 9.4 x 10^{13} centers/cm^3. The amount of injection charges Q_{ij} are fixed by the agreement between the theory and the observation.*

Figure 3 shows dark discharge characteristics for *Digital Photoreceptor HGPC*. The solid cuves were calculated by the mathematical structural trap model with d_s = 0.02 μm, the number of structural units N_L = 15 units, the thermal bulk generation rate G_b = 2.0 x 10^{13} charges/cm^3 s, and depletable center density N_b = 9.4 x 10^{13} centers/cm^3. By agreement between the theory and the observation, surface injection charge densities Q_{ij} were fixed. The photoreceptors were measured under conditions where the gases from the corona charger were not vented. We assumed that corona generated chemicals on the free photoconductor surface increase in accordance with the corona discharge current and as a result surface charge injection also increases.

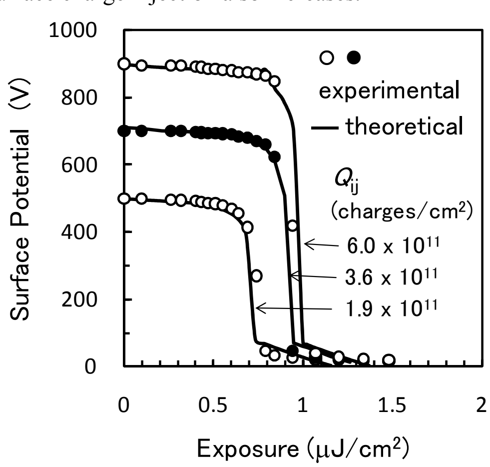

***Figure 4.** Photoinduced discharge characteristics for Digital Photoreceptor HGPC. The photoreceptors were measured under conditions where the gasses from the corona were not vented. Exposure time is 3.6 ms with light of 710 nm. The theoretical curves are calculated with L = 16 μm, d_s = 0.02 μm, N_L = 15 units, η_0 = 0.95 and N_b = 9.4 x 10^{13} centers/cm^3. The injection charges Q_{ij} were determined in Fig. 3.*

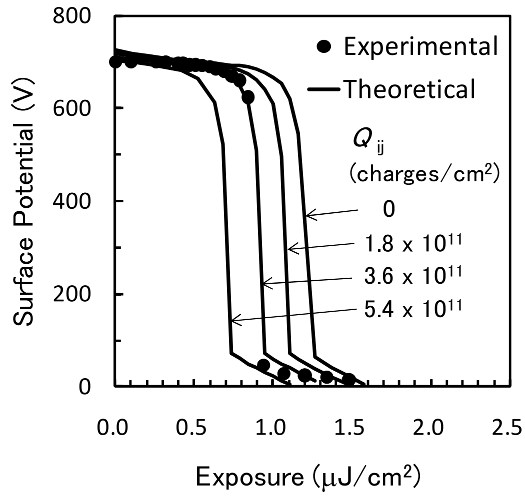

***Figure 5.** Photoinduced discharge characteristics for high gamma photoreceptors simulated with various injection charges Q_{ij}.*

Figure 4 shows photoinduced discharge characteristics for *Digital Photoreceptor HGPC*. The solid cuves were calculated by the mathematical structural trap model with d_s = 0.02 μm, N_L = 15 units, exposure time = 3.6 x 10^{-3} sec, η_0 = 0.95, and N_b = 9.4 x 10^{13} centers/cm^3. The close agreement between the theory and the observation was obtained by using surface injection charge densities fixed by the dark discharge characteristis in Figure 3.

Photoinduced discharge curves for *Digital Photoreceptor HGPC* simulated for various surface charge injection densities are shown in Figure 5. The induction exposures of photoinduced discharge depend on surface charge injection densities. It is found that the surface charge injection appears as not initial surface potential deterioration but as a change in the induction exposure.

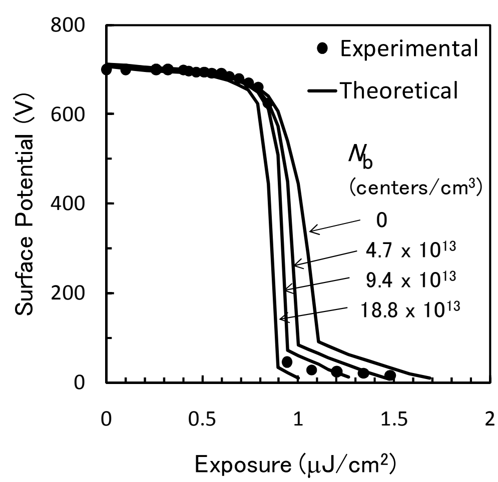

***Figure 6.** Photoinduced discharge characteristics for high gamma photoreceptors simulated with various depletable center densities N_b.*

Photoinduced discharge curves for *Digital Photoreceptor HGPC* simulated for various depletable center densities are shown in Figure 6. The slope of photoinduced discharge curves become steeper with increasing depletable center density. This phenomenon is well described by our strutural trap model. After the free carriers detrap into the next structural trap, these carriers detrap together with the preexisting depletable charges present in the trap. Therefore, as the carrier transport progresses the increasing number of free carriers eventually creates an avalanche discharge. It is found that the depletion phenomenon appears not as an initial deterioration of surface potential but as a rapid photoinduced discharge.

Effect of Overcoat

Figure 6 shows phtoindeuced discharge characterisitics for *Digital Photoreceptor HGPC* with an overcoat layer. The photoreceptors were measured under conditions where the gasses from the corona were not vented but allowed to build up in the apparatus. The solid cuves shown in Figure 5 were calculated by the mathematical structural trap model with $d_s = 0.02$ μm, $N_L = 15$ units, exposure time = 3.6 x 10^{-3} sec, $\eta_0 = 1.3$, $N_b = 9.4 \times 10^{13}$ centers/cm^3, and C_{oc} = 2360 pF/cm^2 (e.g. specific dielectric constant = 4 and overcoat thickness = 1.5 μm), and the residual potential on the overcoat layer V_{ocr} =100 V. The close agreement between the theory and the observation was obtained by using surface injection charge densities $Q_{ij} = 0$. It suggests that the overcoat is effective in protecting the high gamma photoreceptor. Weiss have reported that a single-layer photoreceptor without the overcoat exhibits decreases charge acceptance, however the overcoated photoreceptor is complete stable under the same condition [9].

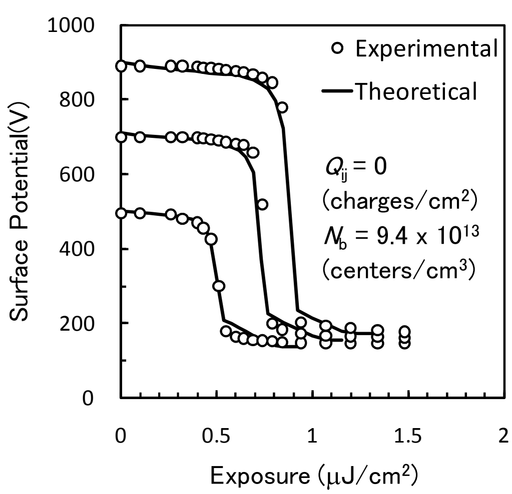

Figure 7. *The effect of an overcoat on the positive corona charging characteristics of Digital Photorecptor HGPC. The photoreceptors were measured under conditions where the gasses from the corona were not vented but allowed to build up in the apparatus. The theoretical curves are calculated with d_s = 0.02 μm, N_L = 15 units, η_0 = 1.3, $N_b = 9.4 \times 10^{13}$ centers/cm^3, C_p = 2360 pF/cm^2, V_{OCR}= 100 V, and the injection charges Q_{ij} = 0.*

Conclusion

We have found that the induction effect is due to an intermediate trapping by structural units on the pigment [2]. We describe a mathematical structural trap model which takes into account both depletion charging and surface charge injection. Based on this model we have clarified the observation that in high gamma photoreceptors as described here, the charge acceptance is not reduced in spite of abundant depletable carriers and excess surface charge injection. The time dependence of the slow dark decay period and the induction exposure change depend on the extent of surface charge injection. An overcoat layer is effective in protecting the high gamma photoreceptor surface from surface charge injection due to corona generated chemicals from corona chargers.

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Kuniki Seino joined Minolta in 1967 and participated in the research and development of photoreceptors such as PVK/Se, CdS·nCdCO$_3$-resin and CuPc/hydrazone/polymer. He received his Dr. Sc. in Physics in 1972 from the Kwansei Gakuin University in Japan. He was named a Senior member of the IS&T in 2002. He was awarded the Imaging Society of Japan Journal Award in 2001 and 2009. He joined Afit as a consulting scientist in 2005.