Aging of Donor Rolls for Single-Component Development in Electrophotography

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The charging and deposition of toners in single-component development have been shown to require efficient dielectric relaxation in the semi-insulating overcoat layer of donor rolls, induced by injection and transport of both polarities of charges. In this paper, the degradation of donor roll performance after repeated usage (aging) is attributed to accumulation of injected charges trapped in the overcoat layer of the rolls. This assertion is quantitatively confirmed by mathematical modeling of toner deposition process.

1. Introduction

In single-component development (SCD) of electrophotographic images, toners are transported by and deposited from the donor rolls. Experimental observations also suggest that toners are predominantly charged during their simultaneous contact with the metering blade and the roll. The typical donor rolls consist of a conductive elastomer shaft overcoated with a thin and more resistive semi-insulator layer. In a previous work,[1] the authors have demonstrated that both the toner charging and deposition steps require efficient dielectric relaxation of the overcoat layer, induced primarily by charge injection from the biased substrate. In the charging step, counter-charges (with polarity opposite to that of toners) are injected to improve the toner charging efficiency. During the deposition step, co-charges are injected to neutralize the counter-charges and to promote the release of toners to the latent images. Therefore, good injections and sufficient mobilities in the overcoat layer for both polarities of charges are essential for successful image development in a time limited by ever increasing print speed.

With the above knowledge, one might infer that the degradation of donor roll performance with usage is caused by the worsening of charge injection and/or charge mobilities. However, in practical usage neither the (charge-injecting) interface at the biased substrate, nor the (charge-transporting) bulk of the overcoat suffers much abuse compared to the other interface (with toner layer). Thus, it is unlikely that the injection and the mobility will change significantly with usage. On the other hand, if the charge lifetime τ (or mobility-lifetime product $\mu\tau$) is small, some of the injected charges can be trapped in the overcoat layer. It may be negligibly small in one charge-deposit cycle, but the effect can become noticeable after trapped charges accumulate with repeating cycles.

The objective of this paper is to examine quantitatively the decrease of toner deposition efficiency that can arise from trapped space charge in the overcoat layer. The mathematical model of the deposition process, described in the next section, is based on the charge transport theory of dielectric relaxation in semi-insulators.[1, 2] It has been successfully applied to various devices and processes in electrophotography in previous publications.[1-5]

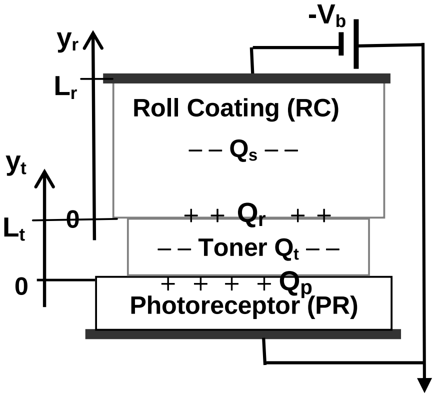

Fig. 1: Layer model of development nip in SCD

2. Toner Deposition Model

In this mathematical model, the configuration at the development nip is represented by a one-dimensional three-layer system shown in Fig.1. The system consists of a biased semi-insulating roll-coating layer (RC), a toner layer and a grounded photoreceptor (PR). The thickness and the permittivity of each layer are denoted by L_k and ε_k, with the subscript k = p, t, and r referring to the PR, toner and RC layers, respectively.

The PR in the dark can be assumed space charge free, with a uniform field E_p across the layer. Hence, the voltage across the layer is $V_p = -E_pL_p$. The toner layer is assumed to have a constant and uniform volume charge

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density q_t. Thus, from Poisson's equation, the field at y_t and the voltage across L_t are given by,

$$E_t(y_t) = E_{t0} + (q_t/\varepsilon_t)y_t \qquad (1)$$

$$V_t = -(E_{t0} + Q_t/2\varepsilon_t)L_t \quad \text{with } Q_t = q_tL_t \qquad (2)$$

where E_{t0} is the toner layer field at the toner/PR interface. In the RC layer, the field $E_r(y)$ and the voltage across the layer V_r can be expressed in terms of the field E_{r0} at the RC/toner interface, the densities $q_p(y)$ and $q_n(y)$ of positive and negative mobile charges, and the density of trapped space charge q_s as,

$$E_r(y) = E_{r0} + \int_0^y [q_p(y') + q_n(y') + q_s]dy'/\varepsilon_r \qquad (3)$$

$$V_r = -\int_0^{Lr} E_r(y)dy = -(E_{r0}L_r + U_r + Q_sL_r/2\varepsilon_r) \qquad (4)$$

where U_r represents the integral,

$$U_r = \int_0^{Lr}dy\int_0^y [q_p(y') + q_n(y')]dy'/\varepsilon_r \qquad (5)$$

The volume density of trapped space charge q_s (after many charging-deposition cycles) is assumed to be uniform and remain unchanged at least during one charging-deposition cycle, and $Q_s= q_sL_r$ is the total trapped space charge per unit area of RC.

Denoting the PR surface charge density by Q_p, and the charge at toner/RC interface by Q_r, Gauss' theorem is used to relate the fields E_p and E_{r0} to E_{t0} as follows:

$$E_p = (\varepsilon_tE_{t0} - Q_p)/\varepsilon_p \qquad (6)$$

$$E_{r0} = (\varepsilon_tE_{t0} + Q_t + Q_r)/\varepsilon_r \qquad (7)$$

Then, equating the sum of voltages V_p, V_t and V_r to the bias voltage $-V_b$, one obtains the fields E_{t0} as,

$$E_{t0} = [V_d - Q_t(D_r + D_t/2) - Q_rD_r - U_r - Q_sD_r/2] /\varepsilon_t(D_p + D_t + D_r) \qquad (8)$$

where $V_d = V_b + Q_pD_p$ is the development voltage, and $D_k = L_k/\varepsilon_k$, with subscript k = p, t, and r, defined above.

For negatively charged toners ($Q_t < 0$), positive E_t is required for toner deposition on PR. A demarcation line that separates the toner layer with $E_t(y_t) > 0$ from that with $E_t(y_t) < 0$ can lie within the toner layer at $y_t = Y_d$, with $E_t(Y_d) = 0$. The ratio of Y_d to the toner layer thickness L_t is a measure of the extent or the "efficiency" of toner deposition. Then, using Eqs. (1) and (8), the deposition efficiency Y_d/L_t is given by,

$$\begin{aligned} Y_d/L_t &= -\varepsilon_tE_{t0}/Q_t \\ &= [Q_t(D_r + D_t/2) + Q_rD_r + U_r + Q_sD_r/2 - V_d] /Q_t(D_p + D_t + D_r) \qquad (9) \end{aligned}$$

This efficiency increases as the mobile charge densities in RC, q_p and q_n, change with time from the initial intrinsic value $\pm q_i$, according to the continuity equations,[2]

$$\partial q_p(y, t)/\partial t = -\partial J_p/\partial y - q_p/\tau_p \qquad (10a)$$

$$\partial q_n(y, t)/\partial t = -\partial J_n/\partial y - q_n/\tau_n \qquad (10b)$$

with, $J_p(y, t) = \mu_pq_pE_r$, and $J_n(y, t) = \mu_nq_nE_r$ (11)

where J_p (or J_n), μ_p(or μ_n) and τ_p (or τ_n) are the positive (or negative) conduction current, charge mobility, and lifetime to deep trapping, respectively. The current injected from the bias is assumed to be proportional to the field $E_r(L_r)$ at the RC/bias contact, $y = L_r$,

$$J_n(L_r) = sE_r(L_r) \qquad (12)$$

where s is a parameter specifying the injection strength. The field E_r is related to the charge densities by Poisson's equation,

$$\partial E_r/\partial y = [q_p(y) + q_n(y) + q_s]/\varepsilon_r \qquad (13)$$

The above set of coupled equations is solved numerically for calculations of the time evolution of the development efficiency Y_d/L_t, Eq.(9).

Table 1 Normalized Units

Unit	Typical value
Length L_o	10^{-2} cm
Permittivity ε_o	$5x10^{-13}$ F/cm
Voltage V_o	10^3 V
Charge mobility μ_o	10^{-5} cm^2/Vsec
Field $E_o = V_o/L_o$	10^5 V/cm
Time: $t_o = L_o/\mu_oE_o$	10^{-2} sec
Charge density /area $Q_o = \varepsilon_oE_o$	$5x10^{-8}$ $Coul/cm^2$
Charge density /vol. $q_o = Q_o/L_o$	$5x10^{-6}$ $Coul/cm^3$
Injection strength $s_o = \mu_oq_o$	$5x10^{-11}$ S/cm

3. Results and Discussion

The results of numerical calculations are presented in a system of normalized units listed in Table 1. The first four (basic) units are used to define the other five (derived) units. The typical values of the units for practical interest in this discussion are also given in the table. The examples discussed in the following figures are calculated with the thicknesses: $L_r = 1$, $L_t = L_p = 0.25$, and the permittivity: $\varepsilon_r = \varepsilon_t = 1$, $\varepsilon_p = 0.25$, in the normalized units of Table 1. However, the conclusions are not affected by these values within the range of practical interest. It is assumed that each deposition starts with RC in equilibrium, $q_p(y) = -q_n(y)$ at all y in RC, and hence, $U_r = 0$ at $t = 0$.

Figures 2 and 3 show the time evolution of deposition efficiency Y_d/L_t (Eq. 9) for the case of fresh rolls, i.e., having no trapped space charge $Q_s = 0$.[1] The lifetimes τ_p and τ_n are assumed to be long enough that no significant trapping occurs in one deposition cycle. In Fig. 2, the five curves correspond to different charge injection strengths s (Eq. 12), but the same sufficiently large hole and electron mobilities, $\mu_p = \mu_n = 1$. In Fig. 3, the five curves differ in the (negative) co-charge mobility μ_n, with a common $\mu_p = 1$ and a sufficient injection $s = 0.3$. The values used for other parameters V_d, q_t, q_i, etc. are given on the figure.

From Figs. 2 and 3, it can be seen that although the asymptotic value (at $t > 1000$) of deposition efficiency is nearly independent on s and/or μ_n, the time it takes to reach the asymptotic value increases by more than an order of magnitude as s or μ_n decreases. In other words, if the development time available is limited (e.g., by increased print speed) to $t = 10 \sim 100t_o$ (typically $t_o \approx 10^{-2}$

sec, Table 1), the deposition efficiency decreases significantly as s and/or μ_n decreases. Both large injection (s) and mobility (μ_n) are needed to provide large amount of co-charges to neutralize the counter-charges Q_r (existing after the toner charging step) and promote toner deposition. On the other hand, the similar calculations as those in Fig. 3, but with decreasing (positive) counter-charge mobilities μ_p, show no reduction in the deposition efficiency across the time range.[1]

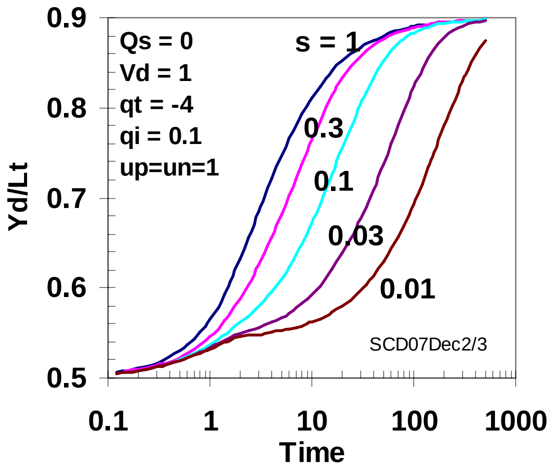

Fig.2: Growth of deposition efficiency Y_d/L_t with time, for various values of injection strength s, for the case of fresh roll, Q_s = 0.

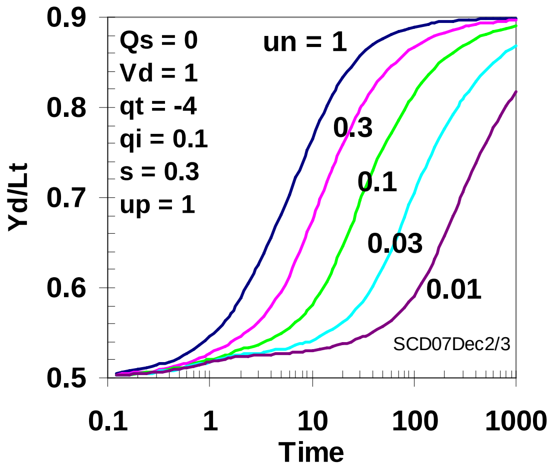

Fig.3: Growth of deposition efficiency Y_d/L_t with time, for various values of (negative) co-charge mobility μ_n, for the case of fresh roll, Q_s = 0.

Based on the above results, the reason for poor toner deposition in fresh rolls can be attributed to weak charge injection from the biased substrate and/or low co-charge mobility. However, the same reason may not account for the performance degradation of initially good rolls after repeated usage, as explained in Introduction. Instead, we would suggest that the poor transport due to short lifetime to deep trapping τ (or small mobility-lifetime product $\mu\tau$) of injected charge could be a reason for the degradation from usage. Such poor transport leads to accumulation of trapped space charge Q_s in the RC layer. The effects of Q_s accumulated from repeated usage are examined in the following figures.

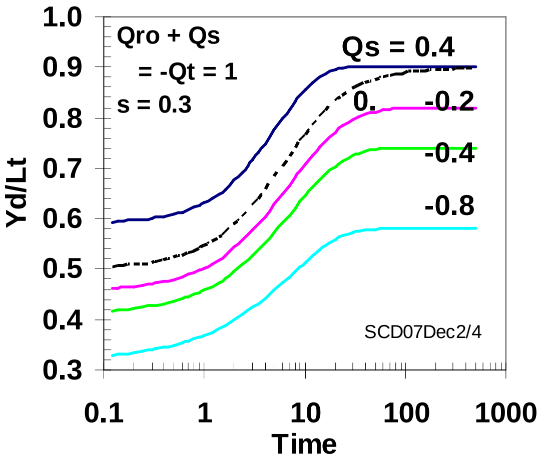

Fig.4: Growth of deposition efficiency Y_d/L_t with time, for different trapped space charge Q_s. Other parameter values are the same as in Fig. 2, except the injection strength is fixed to s = 0.3.

Figure 4 shows the growth of deposition efficiency Y_d/L_t for a moderate injection of s = 0.3 and total toner charge $Q_t = -1$. The growth curves with positive and negative trapped space charge Q_s are compared to that for trap-free case $Q_s = 0$. At the start of deposition, the sum of charges at RC/toner interface, Q_{r0}, and in RC bulk, Q_s, is assumed to be countered by (or equals to the negative of) total toner charges Q_t:

$$Q_{r0} + Q_s = -Q_t \tag{14}$$

When Q_s is negative, the deposition efficiency, shown in Fig. 4, becomes smaller than that in fresh rolls ($Q_s = 0$). For negative toners, negative charges have to be injected into RC during the deposition. If the negative charges do not have sufficient lifetime in RC layer to reach the interface, they are trapped and accumulate in the bulk of RC layer ($Q_s < 0$). This causes a reduction in the deposition efficiency for later cycles as shown in Fig. 4. On the other hand, the positive counter-charges, injected into RC during the toner charging step, are seen to cause no reduction in the deposition efficiency even if they are trapped and accumulate in the RC layer ($Q_s > 0$).

Figure 5 shows the effect of different injection strength s on the deposition efficiencies for rolls with trapped negative space charge, $Q_s = -0.5$, accumulated after repeated usage. The slower growth of the efficiency for smaller injection strength is similar to that shown in Fig. 2 for the case of fresh rolls with $Q_s = 0$. However, the asymptotic value of deposition efficiency (same for all s values) is smaller with trapped space charge $Q_s < 0$.

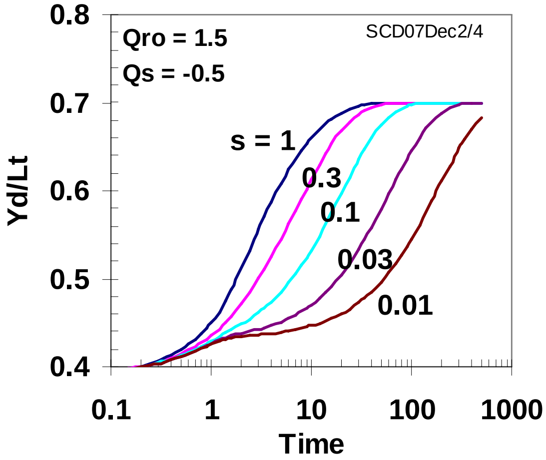

Fig.5: Deposition efficiency Y_d/L_t vs. time, with trapped charge $Q_s = -0.5$, and varying injection strength s. Other parameter values are the same as in Fig. 2.

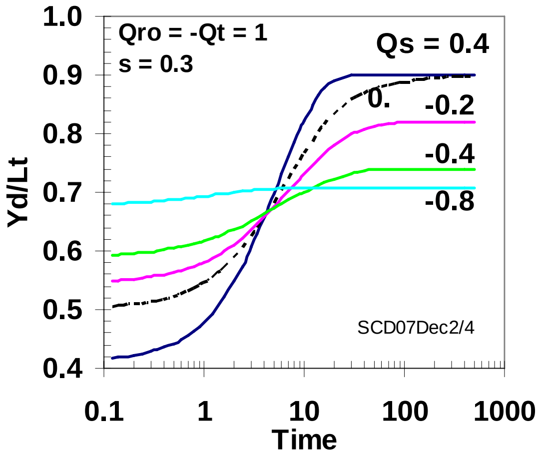

Fig.6: Growth of deposition efficiency Y_d/L_t with time, with different trapped space charge Q_s, but the same initial interface charge $Q_r = -Q_t$. Other parameter values are the same as in Fig. 4.

Due to the constrain of the initial condition Eq.(14), the initial value of (positive) charge at the interface Q_{r0} increases as Q_s becomes more negative. This is a physical reason for the decrease in deposition efficiency. As an alternative initial condition, we can assume Q_{r0} to have a fixed value, e.g., $Q_{r0} = -Q_t$, independent of the Q_s values, (i.e., toner charge countered only by Q_r at t = 0). Figure 6 shows the deposition efficiency calculated under this assumption. As the trapped space charge Q_s becomes more negative, the efficiency at short times (< 10 t_o) is larger, but the asymptotic values (at t >> $10t_o$) decreases, similar to those shown in Fig. 4.

5. Conclusions

Combining the results of the previous[1] and the present analyses, we can conclude that poor performance of fresh donor rolls can be attributed to poor injection and/or small mobility of co-charges. On the other hand, the reason for initially good rolls to become poor after repeated usage (aging) is very likely caused by short lifetime (or mobility-lifetime product) of the injected co-charge in the semi-insulator overcoat layer, leading to accumulation of trapped space charge.

The toner charging step (detailed in Ref. 1) has also been extended to examine the effects of trapped space charges in the overcoat layer. The results indicate that the accumulated (negative) co-charges can have similar detrimental effects on toner charging.

The electrical characterizations of donor rolls (or charging rolls, or transfer media) are often carried out by closed-circuit resistance measurements. However, the nature of the above-mentioned critical parameters, i.e., injection, mobility, and lifetime, cannot be simply related to the measured resistance. On the other hand, the open-circuit measurements of dielectric relaxation simulate more closely the processes in actual electrophotographic applications, and have been proven to be more useful in the characterization of semi-insulator devices for such applications.[6]

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