Electrostatic Transfer of Color Images in Electrophotography

Inan Chen
Quality Engineering Associates, Inc.
755 Middlesex Turnpike, Unit 3, Billerica MA 01821
Tel: 978-528-2034 · Fax: 978-528-2033
e-mail: info@qea.com
URL: www.qea.com

Paper presented at the IS&T's NIP20
International Conference on Digital Printing Technologies
October 31–November 5, 2004, Salt Lake City, Utah

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Inan Chen
Quality Engineering Associates (QEA), Inc.
Burlington, Massachusetts, USA

Abstract

A popular technique in color electrophotography is to transfer the developed toner in two steps. While the principles are the same, the physical properties of the system components differ significantly between primary and secondary transfers, or between primary transfers of first-color toner and second-color toner. The effects of these differences on the transfer fields are quantitatively examined by mathematical analyses.

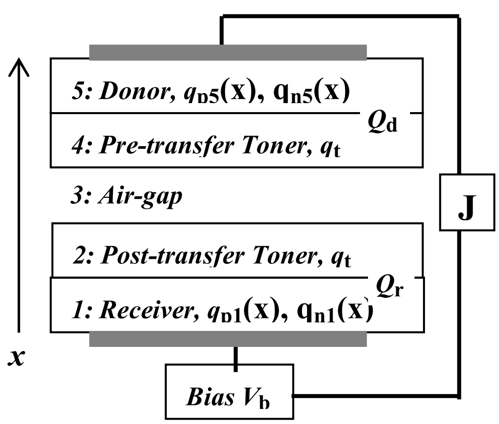

Figure 1. Multi-layer configuration at transfer nip

Introduction

Electrostatic transfer of images from one substrate to another is an important step in electrophotography. A popular technique for this step in color electrophotography is to first transfer the images (toners) developed on a photoreceptor to an intermediate substrate, one color at a time, in the "primary transfer". Then, the accumulated images on the intermediate substrate are collectively transferred to output media in the "secondary transfer". Both transfer steps are based on the same principle. A bias voltage is applied across the multi-layer consisting of the donor, the receiver, the toners, and air-gap, as shown in Fig. 1. A successful transfer requires distributing a large fraction of the applied voltage to the toner layer to be transferred. This is made possible by efficient dielectric relaxation in the receiver and/or the donor, the layers with the largest thickness.[1] While the principles are the same, significant differences exist in the physical properties of the system components involved in these transfer steps. First, the donor in the primary step is an insulating photoreceptor of thickness about 20 µm, whereas in the secondary step it is a semi-insulating intermediate substrate, with good dielectric relaxation, of thickness about 100 µm. Next, the toner layer to be transferred in the secondary step is thicker than that in the primary step (≈10 µm) by a factor of 2 to 4. Furthermore, within the primary steps, the transfer of the second- (and third-, fourth-) color toners differs from that of the first-color toners, because of the existence of previously transferred toner layer on the receiver surface, (Fig. 1). The thickness of this "post-transfer" toner layer is comparable or larger than that of the "pre-transfer" toner layer.

The objective of the present work is to quantitatively examine the consequences of the above-mentioned differences by mathematical modeling. These differences have not been explicitly considered in previous modeling works on electrostatic transfer.[1-8]

Multi-layer Model of Electrostatic Transfer

The configuration at the transfer nip is represented by the one-dimensional multi-layers of Fig.1. The thickness and the permittivity of the k-th layer (k = 1 to 5) are denoted by L_k and ε_k, respectively. The receiver layer (k = 1) and the donor layer (k = 5, in secondary transfer) are semi-insulators that contain mobile charge with volume densities $q_1(x_1)$ and $q_5(x_5)$, respectively, which are functions of position x_k. The air gap (k = 3), the post-transfer (k = 2) and the pre-transfer (k = 4) toner layers are insulators that contain no mobile charges. But the toner layers are assumed to have a constant and uniform volume charge density q_t. The surface charge density at the interface between receiver and post-transfer toner layer is denoted by Q_r, and the corresponding one at the interface between donor and pre-transfer toner layer by Q_d. The field, $E_k(x_k)$, and the voltage V_k across the layer k, can be expressed in terms of these charge densities, thickness and permittivity, and related to one another using Gauss theorem for the electrostatics. These mathematical expressions are derived in Appendix.

The field at the interface between the pre-transfer toner layer (k = 4) and the donor (k = 5) is denoted as "transfer field", E_{tr}. In order to achieve full transfer, E_{tr} must be greater than the field required for toner detachment. It can be shown (in Appendix) that E_{tr} is related to V_4 as,

$$E_{tr} = (Q_{t4}/2 - C_4V_4)/\varepsilon_4 \quad (1)$$

where $Q_{t4} = q_tL_4$ is the toner charge density per area and $C_4 = \varepsilon_4/L_4$ is the capacitance of pre-transfer toner layer.

After the bias V_b is applied, the layer voltages V_k change with time due to dielectric relaxation in the layers. The dielectric relaxation of the multi-layer can be treated by two different approaches using the equivalent RC-circuit model or the space-charge transport model. The former model has been described by many authors.[2-5] In the space-charge model,[1,8,9] we consider the densities of mobile charge $q_k(x_k)$ in the semi-insulating layer k. This includes the receiver (k = 1) and the donor (k = 5, in secondary transfer). The charge transport properties of the layers are specified by the density of intrinsic mobile charges q_{ik} and the charge mobility μ_k. Mobile charges are also supplied by injection from the adjacent electrode. The injection currents from the electrode into the receiver and/or donor layers are assumed to be proportional to the field at the contact x_c as, $J_{inj} = s_kE_k(x_c)$. The proportionality constant s_k (k = 1 or 5) specifies the strength of injection at the contact. Note that s_k has the dimension of conductivity.

Starting with the initial conditions and the boundary conditions (in Appendix), an iterative numerical procedure for the continuity equations is used to calculate the time evolution of charge densities $q_k(x_k)$. The fields $E_k(x)$ and the voltages in each layer V_k are determined from Poisson's equation. Then, the transfer field E_{tr} is calculated from Eq(1).

Transfer Fields, Numerical Results

Examples of numerical results are presented in normalized units listed in Table I. The values of the first four basic units are chosen for convenience to the present application. The values of the other six units follow from their definitions in terms of the basic units. Without loss of generality, negatively charged toners ($q_t < 0$) and positive bias ($V_b > 0$) are assumed in the examples.

Table I: Normalized Units

Length: L_o	(10^{-2} cm)
Time: t_o	(10^{-2} sec)
Permittivity: ε_o	($5x10^{-13}$F/cm)
Voltage: V_o	(10^3 V)
Field: $E_o = V_o/L_o$	(10^5 V/cm)
Capacitance: $C_o = \varepsilon_o/L_o$	($5x10^{-11}$ F/cm^2)
Charge density (area):	
$Q_o = C_oV_o$	($5x10^{-8}$ Coul/cm^2)
Charge density (volume):	
$q_o = C_oV_o/L_o$	($5x 10^{-6}$ Coul/cm^3)
Mobility: $\mu_o = L_o/t_oE_o$	(10^{-5} cm^2/V.sec)
Injection strength (and conductivity):	
$\sigma_o = q_o\mu_o = \varepsilon_o/t_o$	($5x 10^{-11}$ S/cm)

Primary Transfers

Figure 2 shows examples of the time evolution of transfer fields E_{tr}, calculated for typical primary transfers of second-color toners, with the first-color toners already on the receiver. The donor is a discharged insulating photoreceptor. The parameter values are chosen as: $L_1 = 1$, $L_2 = L_3 = L_4 = 0.1$, $L_5 = 0.2$; $\varepsilon_1 = 1$, $\varepsilon_2 = \varepsilon_4 = \varepsilon_5 = 0.5$, $\varepsilon_3 = 0.2$; $q_t = -4$ and $V_b = 1$, all in normalized units of Table I. The conduction and injection properties of the receiver layer are specified by q_{i1}, s_1 and μ values.

The E_{tr} is found to approach an asymptotic value that is independent of the values of transport parameters, q_{i1}, s_1 and μ. With large q_{i1} (>0.1) and/or large s_1 (>0.1), the approach is complete in a few ten units of time t_o (Table I). However, if the nip time is limited, E_{tr} can be significantly smaller with smaller q_i and/or s_1.

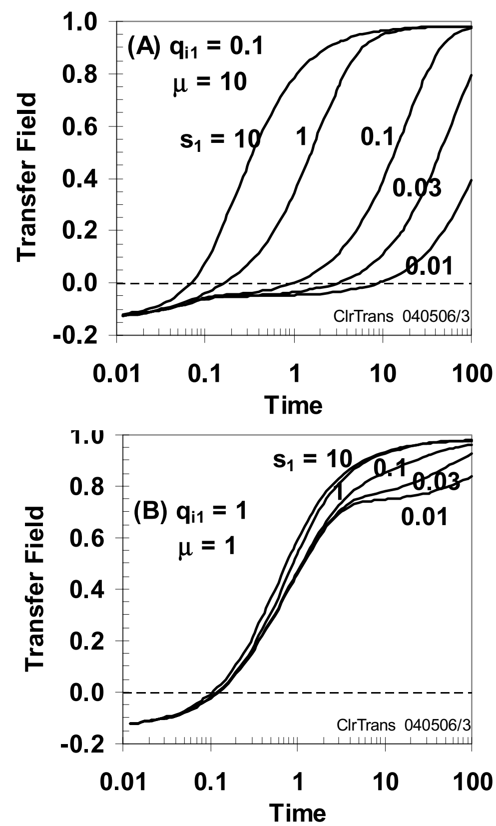

Figure 2. Transfer field vs. time, in primary transfers of second-color, showing dependence on injection strength s_1, charge density q_i and mobility μ.

The ten samples shown in Figs. 2A and 2B have different values of intrinsic charge density q_{i1}, or mobility μ, or injection strength s_1, but the same conductivity $\sigma = \mu q_{i1} = 1$. The E_{tr} values at a given time can be seen to differ significantly, especially with small values of q_i (< 1) and/or s_1 (< 0.1). This is strong evidence that conductivity (or resistivity) is not a sufficient parameter for characterization of transfer media. The three parameters, q_i, μ and s play independent roles on the transfer field. Both q_i and s_1 determine the supply of charge needed for dielectric relaxation by complementing each other, while the mobility determines the time needed for the relaxation.

The dependence of E_{tr} (the asymptotic values) on the thickness of post-transfer toner layer L_2 in primary transfer is shown in Fig. 3 for a receiver with good dielectric relaxation, (q_{i1}= 1, μ = 1 and s_1 =1). The curve with L_2 = 0 corresponds to the transfer of the first-color toners. As the thickness L_2 increases, it requires longer time for the transfer field to become positive (required for the detachment of negative toners), and the asymptotic value is smaller.

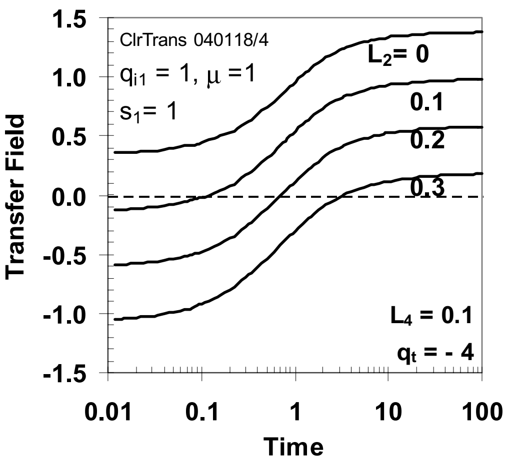

Figure 3. Primary transfer field Etr vs. time, with thickness of post-transfer toner L2 varied.

The results of similar calculations are summarized in Fig. 4 by plotting the asymptotic values of E_{tr} as functions of post-transfer toner layer thickness L_2 and toner charge density q_t. The transfer fields are seen to decrease linearly as the thickness of post-transfer toner layer increases. This indicates that if the bias voltages and the nip dwell time remain the same, the second-color transfer (and the following ones) can be less complete than the first-color transfer. The results in Fig. 4 appear to suggest a merit for lower toner charge density. However, it should be noted that the required detach field for lower charge toners can be larger.[10,11]

Secondary Transfers

In secondary transfers, the donor layer (k = 5) becomes as semi-insulating and as thick as the receiver layer (k = 1). In addition, the (pre-transfer) toner layer thickness L_4 is 2 to 4 times thicker than that in primary transfers, (but L_2 = 0). Figure 5 shows the effects of intrinsic charge density q_{i5} and injection strength s_5 of the donor on the growth of transfer field. The donor thickness L_5 is assumed to be the same as that of receiver, and the toner layer thickness L_4 (multi-color) is twice that of the primary (single color). A first-color primary transfer is also shown by a dashed curve for comparison. The transfer field is seen to need some time to become positive, and the asymptotic value is smaller than that for the primary. The charge transport properties of donor, q_{i5} and s_5, have significant effects on the size of E_{tr}.

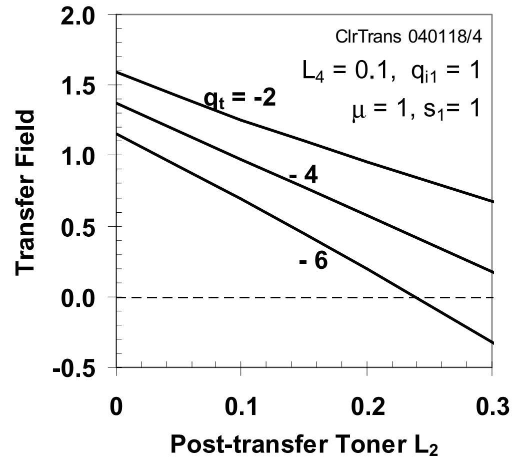

Figure 4. Asymptotic values of primary transfer field vs. post-transfer toner layer thickness, for three values of toner charge density qt.

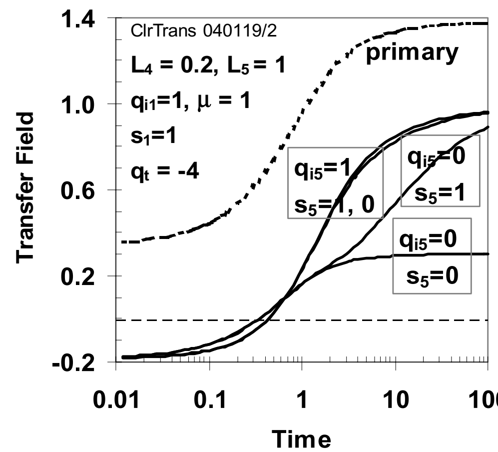

Figure 5. Time evolution of transfer fields in secondary transfer. Intrinsic charge density q_{i5} and injection strength s_5 of donor varied.

Figure 6 summarizes the results of similar calculations. The asymptotic transfer fields are shown as the toner layer thickness L_4, charge density q_t, and the transport properties of donor (q_{i5} and s_5) are varied. The semi-insulating nature of donor in secondary transfer is seen to have a merit of increasing the transfer field. However, this is countered by the increase in the toner thickness L_4 (due to multi-color images). The smaller the toner charge density q_t, the larger the transfer field, as in the primary transfer (Fig. 4).

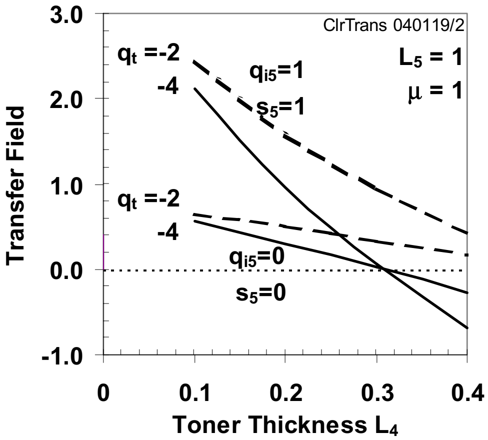

Figure 6. Asymptotic values of secondary transfer field vs. toner thickness L_4 for two sets of toner charge density q_t, and two sets of donor q_{i5} and s_5.

Discussion and Conclusions

Corresponding calculations of transfer fields with the RC-circuit model are also carried out (in Appendix). The features of transfer fields in multi-color primary transfers and secondary transfers are found to be essentially similar to those obtained by the space-charge model, shown in Figs. 3 to 6. Thus, independent of whether the RC-circuit model or the space-charge model is used for analyses, it can be concluded that: (1) In primary transfers, the transfer fields for the second (or higher) color becomes weaker than that for the first color as the thickness of the post-transfer toner on the intermediate substrate increases (Fig. 4); (2) In secondary transfers, the transfer field is enhanced by the donor being a semi-insulator, but weakened by the larger thickness of (multi-color) toners to be transferred (Fig. 6); and (3) Smaller toner charge density increases transfer field (Figs. 4 and 6). However, it should be noted that toners with smaller charge density may require a larger detach field.[10,11]

The RC-circuit model has the advantage of simplicity and familiarity in specifying the electrical property of the layers by their resistances (or conductivity). However, as demonstrated with Fig. 2, conductivity is not sufficient for the determination of transfer field, and the characterization of dielectric relaxation in general. Furthermore, because the electrical contacts to the receiver or the donor (and semi-insulators in general) are not always Ohmic and hence, the resistance is often not a well-defined quantity.

In contrast, the space-charge model specifies the electrical properties in terms of intrinsic charge density q_i, charge mobility μ and injection strength s at the contact. While the resistance is an intrinsic material property, the injection strength s is determined by the nature of interface between two layers. It depends on the fabrication condition and can change with usage. Furthermore, because the intermediate substrate serves as a receiver in primary transfers and as a donor in secondary transfers, the polarity dependence of charge injection and transport makes significant differences. As illustrated in Fig. 7, with negative toners (for example), injection and transport of positive charges are needed for the primary, but those of negative charges are required for the secondary. Because resistance does not specify the charge polarity, it is not sufficient for electrical characterization of transfer media. The transfer fields are seen to have strong dependence on the size of injection, especially for materials with small intrinsic charge density q_i, and/or for limited nip time due to higher process speeds (Figs. 2 and 5).

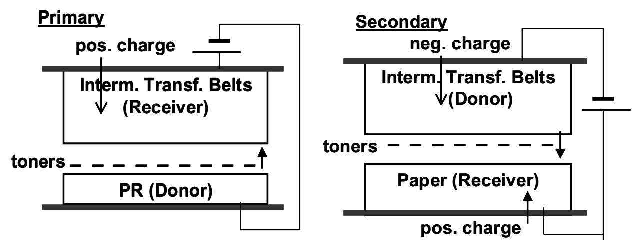

Figure 7. Schematics of charge injection required in primary and secondary transfers.

Strong evidence in favor of the space-charge model is the ability to reproduce the non-exponential decay of voltage observed in many semi-insulator layers. (e.g., Fig. B3 in Appendix). The RC-circuit model predicts the decay to be simply exponential in time. The space-charge model has successfully interpreted the open-circuit characterization of transfer media.[8] The technique, known as "Electrostatic Charge Decay" (ECD) has been shown to provide more reliable evaluation of transfer media performance than the closed-circuit measurements of resistance.[12,13]

Appendix (available on request from the author)

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Biography

Inan Chen received his Ph.D. from the University of Michigan in 1964, and worked at Research Laboratories of Xerox Corp. in Webster, NY, from 1965 to 1998. Currently, he is a consulting scientist at Quality Engineering Associates (QEA) Inc. and others, specializing in mathematical analyses of physical processes, in particular, related to electrophotography. Contact at inanchen@aol.com.