Role of Charge Injection in Electrophotographic Performance of Rollers and Belts

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Abstract

The performance of rollers and belts used in roller-charging, development and transfer sub-processes of electrophotography is known to depend critically on the dielectric relaxation of the semi-insulating layer on the devices. The dielectric relaxation in turn requires efficient charge injection from the biased substrate. Taking into consideration the non-Ohmic nature of the electrical contacts, and the space-charge effects in the transport of injected charges, the impacts of charge injection on dielectric relaxation, and hence, on the device performance are analyzed theoretically. The results of analyses are confirmed by comparing with experimental current and voltage measurements in a characterization technique known as Electrostatic Charge Decay (ECD) method, on samples in use commercially.

Introduction

Devices such as charging rollers, development (or donor) rollers, transfer rollers and intermediate transfer belts used in electrophotography (EP) share a common structure consisting of a semi-insulating dielectric coating on a conductive substrate or core. In EP applications of these devices, the semi-insulator comes in contact with layers of insulators, which can be photoreceptor, toner and/or air, depending on the sub-processes. A bias voltage V_B is applied across the series-capacitors formed by the semi-insulator and the insulator layers, as shown schematically in **Figure 1**.

It has been shown that for good EP performance, the voltage across the semi-insulator layer must relax efficiently during each cycle of the process [1-5]. This "dielectric relaxation" of the semi-insulator shifts most of the bias voltage over to the insulator layer, and promotes the progress and efficiency of the EP process.

In the "equivalent-circuit model" of dielectric relaxation, the dielectric layer is characterized by its resistance R and capacitance C. The voltage across the dielectric layer is expected to decay exponentially with time, with a time constant $\tau = RC$ [6]. Therefore, the simplest characterization of a roller/belt seems to be the measurement of resistance R. However, the R measurement by applying a voltage directly across the layer thickness (i.e., in closed-circuit mode) often yields results fluctuating with the conditions (pressure, smoothness) of the contacts between the electrode and the sample. Furthermore, the measured resistance data are often found to be inconsistent with or unable to predict the EP performance of the devices.

The reason for the failure of roller/belt characterization by resistance measurements can be attributed to the fact that the contact between the semi-insulator and the substrate electrode is generally non-Ohmic, mainly because of the heterogeneous nature of the semi-insulator material. With non-Ohmic contacts, the charge density in the sample is not maintained at the uniform value equal to the sample's intrinsic charge density q_i, but can be more or less depending on how much charge can be injected from the contacts. The amount of charge injected, in turn depends on the pressure and smoothness of the contacts, and the electric field and the charge available at the contacts. In addition, because of the low mobility μ ($\approx 10^{-5}$ cm^2/Vsec, or less) of charges in the semi-insulators, the Coulomb interactions among the charges during the transport (i.e., the space-charge effects) cannot be neglected. Consequently, the charge density $q(x, t)$ becomes position- and time-dependent, and hence, the conductivity $\sigma = \mu q$ or the resistance $R = L/\sigma$ (where L = layer thickness) has no clear and useful physical meaning.

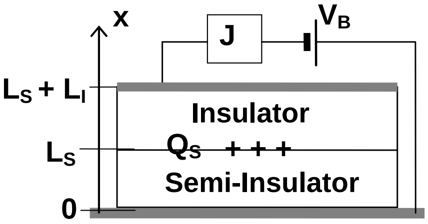

Figure 1. *Series-capacitors configuration of rolls or belts in electrophotographic charging, development or transfer processes.*

An important difference between the resistance measurement and the dielectric relaxation of roller/belt in EP processes is that in the latter case, a constant voltage is applied across both the semi-insulator and the insulator layer, as shown in **Figure 1**. Therefore, the voltage across the semi-insulator is not constant in time (as in resistance measurements). The relaxation actually occurs under a decreasing voltage, i.e., under an open-circuit condition. This can be another reason why the resistance from closed-circuit measurements fails to predict the EP performance.

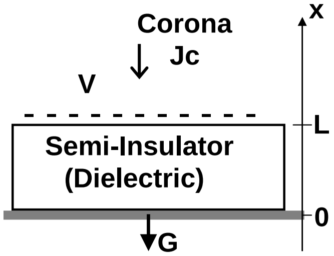

Figure 2. *Schematic of roller/belt characterization by Electrostatic Charge Decay (ECD) technique.*

To simulate the open-circuit condition of dielectric relaxation, we have introduced a characterization technique called "Electrostatic Charge Decay" or ECD [7-9]. A schematic of the ECD method is shown in **Figure 2**. In this method, the test sample on a grounded substrate is charged with corona current on the surface. In addition to the current through the sample to the ground, the changing surface voltage can be measured by means of a non-contact electrostatic probe. In the current measurements, the decrease of corona current with charging time (and with the build-up of surface voltage) is monitored. In the voltage measurements, the surface voltages during and after corona charging are monitored. The measured voltage or current provides evaluation of the dielectric relaxation in the semi-insulator. By scanning the corona source and voltage probe across the sample surface, the technique provides additional advantages of non-destructive, efficient mapping of a large area of the sample for evaluating the uniformity of the device functions.

In the next section, we present the first principle charge transport equations required to describe (and simulate) the dielectric relaxation of semi-insulator in the series-capacitors configuration of **Figure 1** and the ECD technique of **Figure 2**. Numerical examples of the simulations are presented for comparison with experimental results in the succeeding sections.

Charge Transport Equations for Dielectric Relaxation

The motion of charges in the semi-insulator is described by the continuity equation for the positive (or negative) charge densities q_p (or $\mathbf{q}_n$), given by (omitting the subscripts p or n),

$$\partial q(x, t)/\partial t = -\partial J/\partial x = -(\partial/\partial x)(\mu q E) \tag{1}$$

where $J(x, t) = \mu q E$ is the conduction current, μ is the charge mobility and $E(x, t)$ is the electric field in the semi-insulator layer. In the insulator (of **Figure 1**), the charge densities and conduction currents are always zero, and hence, the field E_I is uniform in x. For non-Ohmic contacts, the injection current from the bias is a function of the field $E(0)$ at the contact with substrate, $x = 0$. For lack of better knowledge, it can be assumed to be linearly proportional to the field $E(0)$ with the proportionality constant s specifying the injection strength,

$$J_p(0) = sE(0), \text{ and } J_n(0) = 0 \quad \text{if } E(0) > 0 \tag{2a}$$

$$\text{or, } J_n(0) = sE(0), \text{ and } J_p(0) = 0 \quad \text{if } E(0) < 0 \tag{2b}$$

The field $E(\mathrm{x})$ is related to the charge densities q_p and q_n, and the permittivity ε by Poisson's equation,

$$\partial E(x)/\partial x = [q_p(x) + q_n(x)]/\varepsilon \tag{3}$$

In the series-capacitors (**Figure 1**) the field discontinuity at the interface $x = L_S$ is given by Gauss' theorem,

$$\varepsilon_I E_I - \varepsilon_S E_S(L_S) = Q_S(t) \tag{4}$$

where ε_I and ε_S are the permittivities of the insulator and the semi-insulator layers, respectively, and Q_S is the area charge density at the interface, $x = L_S$.

The voltages V_I and V_S in each layer are given by the integrals of fields, with the boundary condition that the sum is constant and equal to the bias voltage : $V_I + V_S = V_B$.

At $t = 0$, the charge-neutral conditions ($q_p = -q_n = q_i$ and $Q_S = 0$) yield the initial values of fields (uniform in each layer) as,

$$E_S = -V_B/\varepsilon_S(L_S/\varepsilon_S + L_I/\varepsilon_I), \quad E_I = -V_B/\varepsilon_I(L_S/\varepsilon_S + L_I/\varepsilon_I) \tag{5}$$

In the ECD experiments (**Figure 2**), the boundary condition at the surface is given by the corona current J_C, represented by,

$$J_C(t) = J_{mx}[1 - V(t)/V_{mx}] \tag{6}$$

where $V(t)$ is the surface voltage at time t, J_{mx} and V_{mx} are two empirically determined parameters of the corona device, representing the initial current (at $V = 0$), and the saturation voltage (at $J_C = 0$). The surface charge density $Q_S(t)$ varies with time as J_C deposits charges on the surface, and the positive or negative conduction currents J_p or J_n in the layer arrives at the surface:

$$dQ_S/dt = -J_C(t) + J_p(L, t) + J_n(L, t) \tag{7}$$

The field at the surface $x = L$ is related to Q_S by Gauss' theorem: $\varepsilon E(L, t) = -Q_S(t)$, where ε is the sample permittivity. The injection of (corona) charge from the surface into the semi-insulator is practically negligible. The initial conditions for the surface voltage, the field and the corona current are, respectively:

$$V(0) = 0, \; E(x, 0) = 0, \text{ and } J_C(0) = J_{mx} \tag{8}$$

Starting from the initial conditions, Eq.(5) or Eq.(8), the above set of equations can be solved by numerical iteration for the voltages and/or currents as functions of time, to simulate the dielectric relaxation in the series-capacitors or in the ECD experiments. Representative numerical examples of the results are presented and discussed in the following section. These examples are expressed in a system of normalized units listed in a table in the Appendix. A set of typical values of the units for the problems under discussion are also listed.

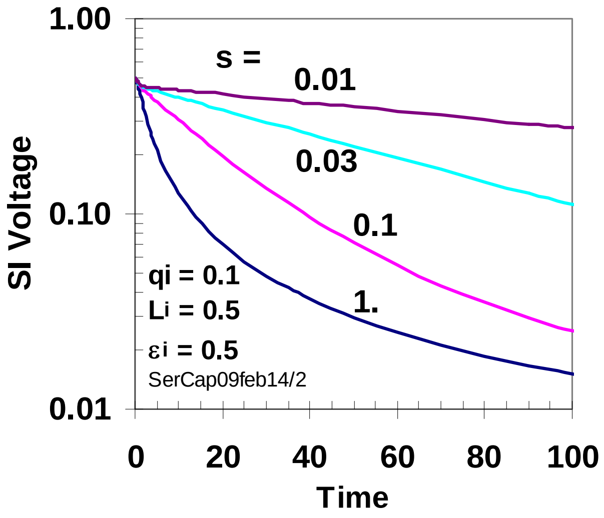

Figure 3. *Dielectric relaxation of the semi-insulator in series-capacitors of Fig.1, for different injection strength s from the substrate.*

Simulation Results

An example of the simulated dielectric relaxation in the series-capacitors (**Figure 1**) is shown in **Figure 3**. The time dependence of voltage across the semi-insulator is shown for different injection strengths s (defined in Equation 2). The intrinsic charge density q_i and the charge mobilities μ_p and μ_n, and hence, the (nominal) resistance $R = L_S/(\mu_p - \mu_n)q_i$ have the same value for all cases. In spite of this, the voltages decay faster with larger injection strength s. Furthermore, the decays deviate from exponential in time after a short time, in disagreement with the prediction of the equivalent-circuit model. These curves are calculated with V_B, L_S, ε_S, μ_p and $-\mu_n$ having the unit values in the normalized unit system listed in Appendix. A small value for q_i (= 0.1) is chosen to represent the semi-insulator. The thickness and permittivity of the insulator are chosen as $L_I = 0.5$, $\varepsilon_I = 0.5$, so that the two layers have the same capacitance $C = \varepsilon/L$. However, the above conclusions hold true, independent of these parameter values within the ranges of practical interest.

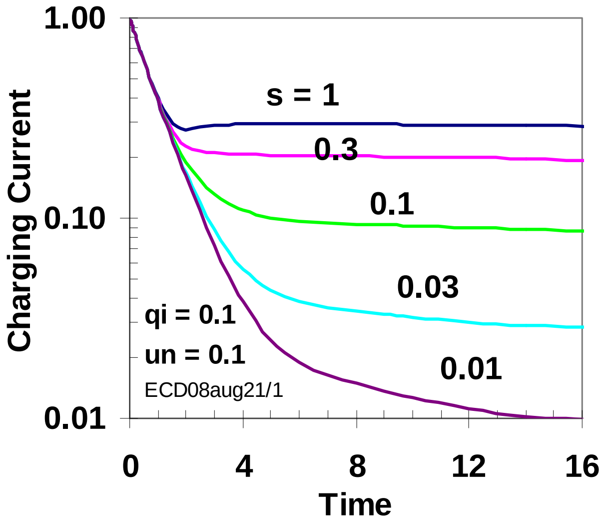

Figure 4. *Decay of corona current with charging time in ECD experiments (Figure 2), for different injection strength* **s**.

It should be noted that the semi-insulator voltage in these series-capacitors is difficult (if not impossible) to measure experimentally. In contrast, the currents and voltages in the ECD experiments (**Figure 2**) can provide more easily the similar features of dielectric relaxation in semi-insulator under the same open-circuit condition. **Figure 4** shows the simulated decrease with time of corona charging currents for samples with different values of injection strength s from the substrate. The currents are seen to decay to steady state values different for different values of s.

The similar dependence on the injection strength s can also be seen in the build-up of surface voltage under corona charging. This is shown in **Figure 5**. In all cases, the voltages reach the saturation values in about 10 units of time (t_o in Appendix).

In practice, the voltages in ECD experiments are measured with a probe located a short distance behind the corona charger, which scans across the sample surface. The corona charges the sample to near the saturation voltage, and the probe measures the decay of voltage afterward. The simulation results of this process are shown in **Figure 6**. The charging time is assumed to be $t = 10t_o$. The decaying voltages approach different (pseudo) steady state values for different s values.

The above simulated results for the ECD currents and voltages are compared with experimental results in the next section.

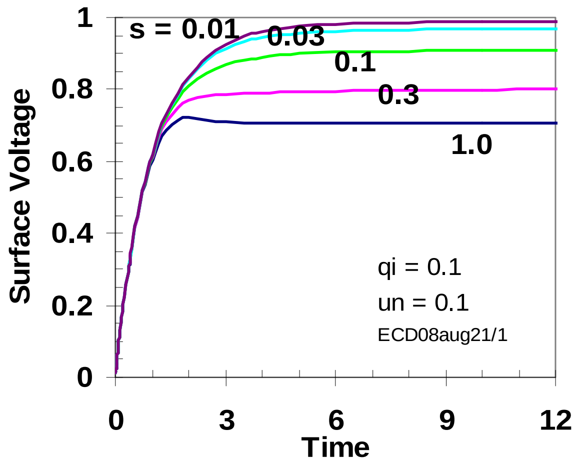

Figure 5. *Growth of surface voltage in ECD experiments (Figure 2), with different injection strengths* **s** *from the substrate.*

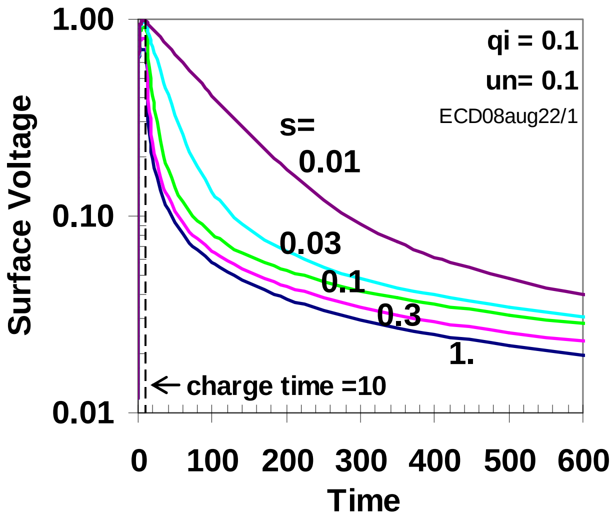

Figure 6. *Decrease of surface voltages after corona charging in ECD experiments, for samples with different injection strengths* **s** *from the substrate.*

Experimental Results

Figure 7 shows examples of measured ECD charging currents as they approach the saturation values. Similar approaches to steady state values of the measured decaying voltages are shown in **Figure 8**. In both figures, the saturation values of currents or voltages are clearly distinguishable from sample to sample, and from position to position within a sample. Based on the simulation results of the previous section, these differences can be attributed to different injection strengths. The ECD current and/or voltage data correlate to the electrophotographic performance of these devices.

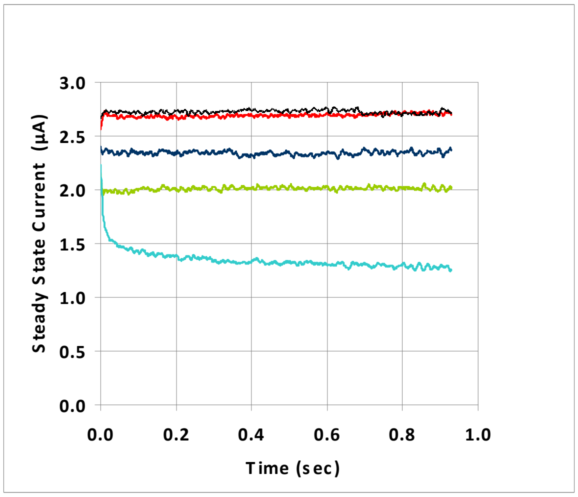

Figure.7. *ECD experimental results of charging currents for various samples, showing the approaches to distinct saturation values.*

Summary and Conclusions

Based on the understanding that dielectric relaxation of the semi-insulator layer is the most important physics underlying the performance of rollers/belts in EP, a mathematical model of dielectric relaxation is introduced. The model is based on the first principle charge transport equations, taking into consideration the non-Ohmic nature of the contact at the substrate (or core), and the Coulomb interaction among moving charges. The model is applied to the series-capacitors configuration which is common to roller-charging of photoreceptors, and charging, development and transfer of toners. It is also applied to the ECD experiments designed for an efficient characterization of rollers/belts, under an open-circuit condition as in those EP sub-processes. In both cases, it is demonstrated that a stronger injection of charges from the contact into the semi-insulator significantly increases the efficiency of dielectric relaxation in the semi-insulator. In the case of ECD experiments, the injection strengths and hence, the efficiencies of dielectric relaxation are depicted by the (easily observable) steady-state values of charging currents and/or the decaying voltages. This confirms the unique advantage of the ECD technique as a characterization tool for the rollers/belts in electrophotography.

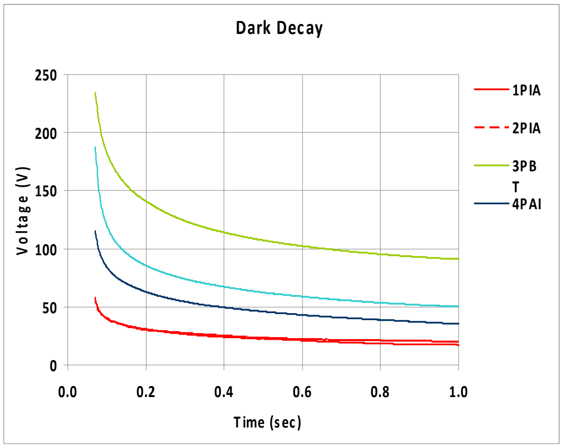

Figure 8. *ECD experimental results for various samples of voltage decay after corona charging, showing the approaches to distinct saturation values.*

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Author Biography

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Appendix: Table of Normalized units

Units	Typical Values
Basic units:	
Length or thickness: L_o	10^{-2} cm
Permittivity: ε_o	3×10^{-13} F/cm
Voltage: V_o	10^{3} V
Charge mobility: μ_o	10^{-5} cm^2/Vsec
Derived units:	
Field: $E_o = V_o/L_o$	10^{5} V/cm
Time: $t_o = L_o/\mu_o E_o$	10^{-2} sec
Charge density/area: $Q_o = \varepsilon_o E_o$	3×10^{-8} Coul/cm^2
Charge density/vol.: $q_o = Q_o/L_o$	3×10^{-6} Coul/cm^3
Current density $J_o = Q_o/t_o$	3×10^{-6} Amp/cm^2
Injection strength: $s_o = \mu_o q_o$	3×10^{-11} S/cm