Photoconductor Implications in Digital Electrophotography*

S. Jeyadev† and Damodar M. Pai†

Xerox Corporation, Webster, New York 14580

The nature of the electrophotographic image when dual-layer organic photoconductors are exposed to digital input is different than that of images obtained with analog input on account of several considerations: (1) reciprocity, (2) space-charge-limited discharge, (3) optical interference effects, and many others. Reciprocity and space-charge-limited conditions result from short exposure times. Reciprocity refers to the change in the efficiency of the supply of carriers from the generator layer into the transport layer. Although, on the basis of theoretical considerations, there could be either an increase or a decrease of supply efficiency, most published results show a reduction in sensitivity. This reduction has been ascribed to Langevin recombination effects. In the limit of space-charge-limited discharge, there is considerable lateral motion of the charge carriers (due to their mutual Coulomb repulsion) during their transit through the transport layer, resulting in loss of resolution, which can also occur in analog exposure through electric field distortion during exposure. Coherent light interference leads to a print pattern in the background.

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Introduction

Considerable progress has been made in the last two decades on the identification of new materials for layered photoconductor devices employed in electrophotography.[1,2] Very highly sensitive pigments with quantum efficiencies close to unity have been developed. Charge transport molecules with trap-free transport and with adequate stability and mobility for most current applications have been identified. Considerable progress has been made on the scientific side in some areas of device operation.

The operation of the device involves absorption of photons, photogeneration of free carriers, and injection of the free holes from the generator layer into the transport layer, followed by charge transport of the injected holes through the transport layer. Processes prior to the photogeneration step have been elucidated in many pigments.[3,4] Very little work has been devoted to understanding the charge injection from the generator layer into the transport layer. The bulk of the scientific effort has been to explain the many unique features of charge transport in disordered systems, such as those employed as charge transport layers.[2]

An area of scientific enquiry that has received less attention and yet is of considerable importance in digital electrophotography is the behavior of the photoconductors when exposed to very short, intense flashes of light. Photoconductor characterizations are generally carried out in an analog mode, in which light exposure is carried out through a mechanical shutter with exposure times of tens of milliseconds. In digital electrophotography, assuming 300- × 300-dpi resolution in an 8.5- × 11-in. copy, the laser exposure time is about 20 ns. A typical photon flux required to discharge a photoconductor is 10^{12} photons/cm^2. Therefore, the photon intensities are, respectively, 10^{14} photons/cm^2-s and 10^{20} photons/cm^2-s in scanners employed to characterize photoconductors and in digital electrophotography. Assuming that in digital electrophotography the carriers are produced "instantly" and further assuming a generator layer of 1-μm thickness, the carrier densities can be as high as 10^{23} photons/cm^3-s in. digital applications.

Short exposure times and large carrier densities could result in two phenomena that would alter the supply efficiency, one that would increase the sensitivity and one that would decrease the sensitivity.[5] In most layered devices, the photogeneration step is field-dependent when characterized in scanners containing exposure light sources of milliseconds duration; a laser flash of short duration should therefore result in all carrier production at the initial field and thus in increased sensitivity. The second phenomenon resulting from the presence of high carrier densities is the increased recombination rate, resulting in a loss of sensitivity. The increase or decrease of sensitivity also involves drastic change in the shape of the photo-induced discharge characteristic (PIDC) curve. A third phenomenon that results from laser flash exposure is the space-charge-limited transport during the hole transit through the transport layer. The charge pattern expands because of mutual Coulomb repulsion, resulting in growth of the charge pattern that gives rise to a loss of resolution in the latent image.[6–8]

In this study several of these consequences of photoconductor behavior when exposed to high intensity laser exposure of short duration are reviewed.

Low Light Intensity Reciprocity Failure

The supply efficiency of a layered organic photoconductor is defined as the number of carriers injected into the transport layer per absorbed photon. The supply efficiency is generally electric-field-dependent, and the shape of the PIDC curve reflects this field dependence. The supply efficiency is the product of photogeneration efficiency and injection efficiency. Generally, both photogeneration and injection efficiencies are electric-field-dependent. The electric-field dependencies of these efficiencies are measured under small signal conditions or in a scanner employing low-intensity light exposures. It would appear then that if the light duration and the times associated with photogeneration processes are short compared with times associated with injection processes, all carriers would be photogenerated at the initial field E_0, even under large

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† IS&T Member

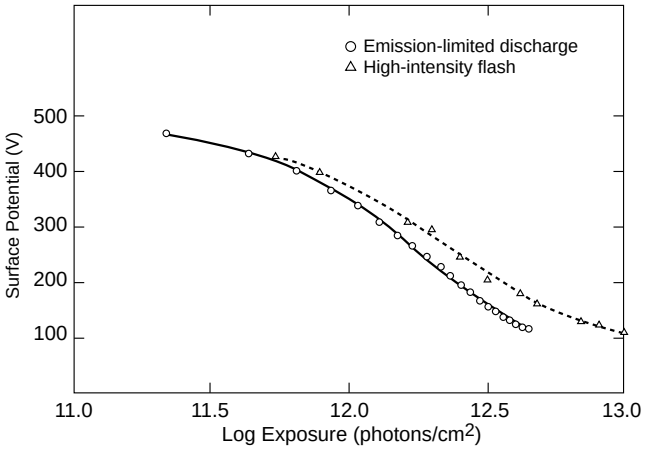

Figure 1. PIDC of an aggregate photoconductor when charged to a positive potential of 500 V and exposed to light of 680-nm wavelength. Loss of efficiency is observed when the photoconductor is exposed to a high-intensity flash. (From Ref. 5.)

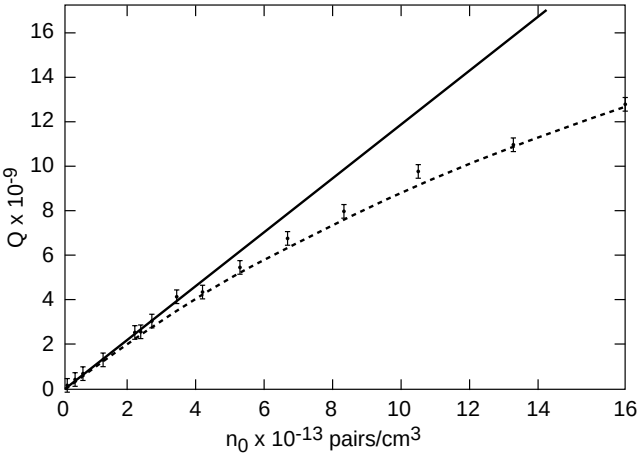

Figure 2. Absolute number of coulombs collected as a function of initial concentration in PVK:TNF film of 18-μm thickness and exposed to a radiation of 693.4-nm wavelength. The applied field is 1.1×10^5 V/cm. (From Ref. 9.)

signal conditions. Therefore, if the PIDC curve were measured with laser exposure of short duration (and by varying the light flux), photogeneration efficiency would be field-independent and the absolute value of the efficiency would be equal to the value measured at E_0 with light exposures of longer duration. In the absence of any injection and recombination issues, the PIDC curve is a straight line with a constant slope. There has not been any published literature showing that the increase in efficiency due to this mechanism has been unambiguously observed. In the published data,[5,9,10] this phenomenon of high field generation has been accompanied, and therefore masked by, a loss mechanism due to carrier recombination described in the next section. The analysis described here suggests that in devices employing extrinsic pigments one should be able to observe the high field generation in the absence of the recombination described in the next section.

High Light Intensity Reciprocity Failure

Two instances of reciprocity failure at high intensity have been reported in the literature. One is with an aggregate organic photoconductor (Fig. 1),[5] and the second one is with the charge transfer complex of poly-*N*-vinyl carbazole (PVK) and trinitrofluorenone (TNF) (Fig. 2).[9] In both these cases the reciprocity failure has been ascribed to Langevin recombination.[11–13] Before commenting on the validity of the application of Langevin recombination, a simple picture and a mathematical expression are described.

Langevin Recombination. Langevin theory deals with recombination under a diffusion-controlled process and was originally proposed for the recombination of gaseous ions. Langevin recombination is a free-carrier recombination, as opposed to geminate recombination, which is the recombination between a hole and an electron produced by the same photon. The theory is based on the assumption that the carrier mean free path is small compared with a critical recombination radius r_c. The term r_c is defined as that distance at which the potential energy of the hole is equal to its kinetic energy kT. The term r_c is obtained from $e^2/4\pi\varepsilon r_c = 3/2kT$, where ε is the permittivity. SI units are employed. Once the hole is trapped in the Coulomb field of an electron, it will lose sufficient energy by phonon interactions to make recombination highly probable. Langevin recombination has been used to explain data in a variety of materials, and the following nomenclature closely follows that given by Hughes to explain recombination data in PVK:TNF.[9]

The predicted recombination coefficient, γ, depends on the relative drift velocities of electrons and holes in the Coulomb field and is given by

$$\gamma = e(\mu_e + \mu_h)/\varepsilon, \tag{1}$$

where μ_e and μ_h are electron and hole drift mobilities, respectively. If carriers of both signs are generated uniformly in space by a light flash, the two drift in opposite directions under the influence of an applied electric field in a photo-generation region of thickness d and volume v_0. If the applied collection field can be considered to be a constant (which is not the case in commercial electrophotography), then the hole and electron carrier distribution will be swept apart at a rate

$$\frac{dx}{dt} = (\mu_e + \mu_h)E, \tag{2}$$

where E is the electric field.

The volume v_r in which the recombination can occur decreases with time in a plane parallel geometry,

$$v_r = v_0(1 - \mu E t / d), \tag{3}$$

where $\mu = (\mu_e + \mu_h)$. Under the assumption that the collection field is constant, the electron and hole distributions are separated after a time $t_0 = d/\mu E$, at which point recombination ceases.

In the overlap region, recombination proceeds at a rate determined by

$$\frac{dn}{dt} = -\gamma n^2, \tag{4}$$

where n is the concentration of holes and electrons in the recombination volume. In the absence of an applied field, the concentration of carriers would decrease with time as

$$n = \frac{n_{gen}}{(1 + \gamma n_{gen} t)}, \tag{5}$$

where n_{gen} is the number of charges at $t = 0$, i.e., the number of charges generated by the flash exposure.

The total number lost through recombination is given by

$$N = \int_0^{t_0} \gamma n^2 v_r(t) dt, \tag{6}$$

where t_0, defined earlier, is the time at which recombination ceases.

From Eqs. 2 through 6, the fraction that escapes recombination is given by

$$\frac{n}{n_{gen}} = \frac{\mu E}{n_{gen}\gamma d} \ln\left(1 + \frac{n_{gen}\gamma d}{\mu E}\right). \tag{7}$$

Equation 7, first derived by Kepler and Coppage[12] and extended by Hughes,[9] can be rewritten in a form more suitable for xerographic applications. Using Eq. 1, we see that

$$\frac{\mu E}{n_{gen}\gamma d} = \frac{\varepsilon E}{n_{gen} e d}. \tag{8}$$

In a xerographic experiment however, εE is just the initial charge density on the photoconductor surface, Q_0, and $en_{gen}d$ is just the areal charge density generated by the flash, which we will denote by Q_{gen}. Thus, defining the ratio

$$f = Q_{gen} / Q_0, \tag{9}$$

we can rewrite Eq. 7 as

$$\frac{n}{n_{gen}} = \frac{1}{f} \ln(1 + f). \tag{10}$$

Physically, f is just the fraction of the initial surface charge density Q_0 that is generated by the flash exposure.

As pointed out at the outset of the derivation, Eq. 7, and hence Eq. 10, we assume that the electric field responsible for sweeping out the charges from the bulk of the photoconductor is independent of space and time. In the xerographic mode this assumption breaks down as Q_{gen} begins to become comparable with or to exceed Q_0, i.e., when the number of generated charges is of the order of, or greater than, "a CV's worth" of charge (where C is the capacitance per unit area). Thus, as noted by Chen,[14] these formulas are correct only in the case of emission-limited discharge. To correctly describe the space-charge-limited case as well, the derivation must be modified to include the effects of the reduction in the field in the recombination region due to the screening of the surface charges by the charges that have been swept out of the recombination zone. We give below a simplified version of the derivations of Fox[13] and Chen[14] that highlights the differences from the results of Refs. 9 and 12.

The derivation is greatly simplified by the critical observation by Fox[13] that during the time the charge distributions are recombining and separating there is no net charge in the recombination volume. For this reason the electric field in the recombination region is constant in space, though it decays with time as the generated charges that have left the recombination region screen the applied field according to

$$\varepsilon \frac{dE}{dt} = -\mu n E. \tag{11}$$

Equation 11 is the usual "open circuit" Maxwell equation: The right-hand side is the total conduction current leaving the recombination volume, and the left-hand side is the displacement current within the volume. Using Eq. 5 in Eq. 11 we obtain

$$E(t) = \frac{E_0}{(1 + \gamma n_{gen} t)} \tag{12}$$

within the recombination volume. If $x(t)$ is the thickness of the volume at time t, the rate at which the volume shrinks is given by

$$dx / dt = -\mu E. \tag{13}$$

Using Eq. 12 in Eq. 13 we get

$$x(t) = d\left[1 - \frac{\ln(1 + \gamma n_{gen} t)}{f}\right]. \tag{14}$$

The time when the recombination ends, t_0, is then given by $x(t_0) = 0$, i.e.,

$$t_0 = (e^f - 1) / \gamma n_{gen}. \tag{15}$$

The number lost to recombination per unit area is given, in analogy to Eq. 6, by

$$Q_R = \int_0^{t_0} (\gamma n^2) x(t) dt. \tag{16}$$

Inserting Eqs. 5 and 14 into Eq. 16, we obtain

$$Q_R = Q_{gen}\left(1 - \frac{1 - e^{-f}}{f}\right). \tag{17}$$

Thus, the fraction that escapes recombination and contributes to the discharge, $Q_{gen} - Q_R$, can be written, in analogy to Eq. 7, as

$$n / n_{gen} = 1 - Q_R / Q_{gen} = (1 - e^{-f}) / f. \tag{18}$$

Alternatively, we can write

$$Q_D = Q_0(1 - e^{-f}), \tag{19}$$

where Q_D is the charge per unit area that goes to discharge the photoconductor.

In writing down the PIDCs, we assume that all of the charges that escape recombination neutralize the corresponding surface charges, which is true if the charges have sufficient time to transit the sample. In a practical measurement, the surface voltage of the photoconductor is measured after a finite time, and charges may still be in transit in the bulk of the sample at this time. Because the discharge is not complete, deviations from the expressions given below for the PIDCs may be observed. This transit time limitation manifests itself as an additional slowing down of the PIDC, and it must be accounted for if the measurements are to be used to study the effects of reciprocity failure due to Langevin recombination.[15]

We are now in a position to express the PIDC for photoconductors subjected to very short flash exposures in which Langevin recombination occurs. From Eq. 19 we see that the charge on the photoconductor surface will be

reduced from the initial value of Q_0 to $Q_0 - Q_D = Q_0 e^{-f}$, and hence the final voltage will be

$$V = V_0 e^{-f} = V_0 e^{-(Q_{gen}/Q_0)}. \tag{20}$$

If all the charges are generated at the initial field, we can write the PIDC as

$$V(X) = V_0 e^{-(e\eta_0 X/Q_0)}, \tag{21}$$

where X is the exposure in photons/unit area and η_0 is the *generation* efficiency at the initial field. *The exponential PIDC in Eq. 21 is characteristic of high field generation followed by Langevin recombination, and it is universal in the sense that it is valid for all materials in which these experimental conditions can be achieved*. For the purposes of illustrating the effects of Langevin recombination on the PIDC, we have assumed that there are no field-dependent charge injection issues—an assumption that may not be true in layered photoconductors. The *supply* efficiency $\eta_{sup}(E)$, which determines the shape of the PIDC curve, is the product of the photogeneration efficiency, $\eta_{gen}(E)$, and the injection efficiency from the generator layer into the transport layer, $\eta_{inj}(E)$. The high field photogeneration and Langevin recombination issues discussed here affect only $\eta_{gen}(E)$. The universality of the shape of the PIDC curve (Eq. 21) in the presence of high field photogeneration followed by Langevin recombination is applicable if $\eta_{inj}(E) = 1$. In general, $\eta_{inj}(E)$ is less than unity and is dependent on electric field and device material composition. Therefore, the actual PIDC shape in the presence of high field photogeneration followed by Langevin recombination is slower than that predicted by Eq. 21. We make the same assumption, i.e., $\eta_{inj}(E) = 1$, when we compare the Langevin PIDC to those obtained using low-intensity exposures. If we use Hughes' expression for the fraction of carriers that escape recombination (Eq. 10), we obtain

$$V_H(X) = \begin{cases} V_0\left[1 - \ln(1 + e\eta_0 X/Q_0)\right] & \text{for } X \le (e-1)Q_0/e\eta_0 \\ 0 & \text{for } X > (e-1)Q_0/e\eta_0 \end{cases} \tag{22}$$

for the PIDC where we have used the high field generation value for f, $f = Q_{gen}/Q_0 = e\eta_0 X$. Note that if the generated charge exceeds the critical value $(e-1)Q_0 \sim 1.78\,Q_0$, the photoconductor will discharge completely. This is not the case when Fox's expression Eq. 20 is used.

In the emission-limited case the PIDC is defined by

$$dV/dX = -(e/C)\eta(V), \tag{23}$$

where C is the capacitance per unit area of the device and $\eta(V)$ is the field-dependent supply efficiency expressed in terms of the surface potential of the device. Knowledge of this quantity allows us to integrate Eq. 23 and obtain the PIDC. Two special cases of interest to us are when $\eta(V)$ is: (1) field-independent and (2) linearly dependent on field. However, it is more instructive to consider first the general case where $\eta(V)$ is a power law:

$$\eta(V) = \eta_0 (V/V_0)^p. \tag{24}$$

In this case the PIDC is given by

$$V(X) = V_0 \begin{cases} \left[1 - \dfrac{e(1-p)\eta_0 X}{Q_0}\right]^{1/(1-p)} & \text{for } p \ne 1 \\ e^{-(e\eta_0 X/Q_0)} & \text{for } p = 1. \end{cases} \tag{25}$$

For $p = 0$ the supply efficiency is field-independent (see Fig. 4), and the PIDC is a straight line, as shown in Fig. 5. For $p = 1$, the field-dependence is linear and the PIDC is exponential in the exposure, X. *Note that for the case of linear field dependence the emission-limited PIDC is exactly the same as in Eq. 21, even though Eq. 21 results from high-intensity flash exposure followed by Langevin recombination, whereas the expression in Eq. 25 arises from linear field dependence and the absence of recombination in an emission-limited situation. Thus those special systems in which the field dependence of the supply efficiency is linear with the field and in which carriers can undergo Langevin recombination at high densities can be expected to display reciprocity*. This effect has been demonstrated by Buettner and Mey[10] for the Kodak Ektavolt recording film SO-102 (Fig. 3), which satisfies these conditions. Note also that when $p < 1$, the photoconductor is completely discharged at a finite exposure given by

$$X_{tot} = Q_0/e\eta_0(1-p), \qquad \text{for } p < 1. \tag{26}$$

For the purposes of comparing the PIDCs resulting from high- and low-intensity exposures, one may, following Eq. 23, define an effective supply efficiency for flash exposures followed by Langevin recombination as

$$\eta_L(V) = -(C/e)dV/dX, \tag{27}$$

where $V(X)$ can be either the PIDC given by Fox and Chen, namely Eq. 21, or that derived from Hughes' expressions, i.e. Eq. 22. Thus we get the effective supply efficiency for high-intensity flash exposures

$$\eta_L(V) = \eta_0 \begin{cases} V/V_0 & \text{Fox and Chen} \\ e^{V/V_0 - 1} & \text{Hughes} \end{cases}. \tag{28}$$

The effective supply efficiency (or yield) given in Eq. 28 is due to the recombination losses, and we will interpret it as a sensitivity loss.

The sensitivity loss as a result of Langevin recombination, $\eta_L(V)$, is plotted in Fig. 4 for an imaginary photoconductor. The abscissa is the normalized potential V/V_0 (with Point 1 corresponding to the initial potential and 0

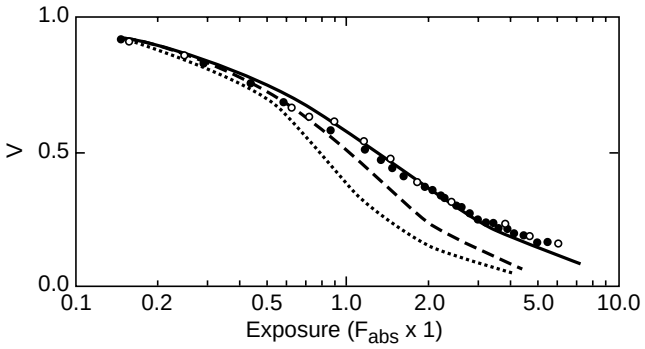

Figure 3. Calculated PIDC curves versus experimental results for a Kodak Ektavolt recording film SO-102. The light is absorbed in the bulk of the film and only holes are mobile. Low-intensity exposure data are shown by solid circles, and open circles are for high-intensity laser flash exposures. Reciprocity is observed. The solid line represents the fit for the experimental data points. The dotted line and the dashed line are the calculated PIDCs for emission-limited and flash exposure cases, respectively, in the absence of recombination for a bulk absorption system with only one mobile charge species. (From Ref. 10.)

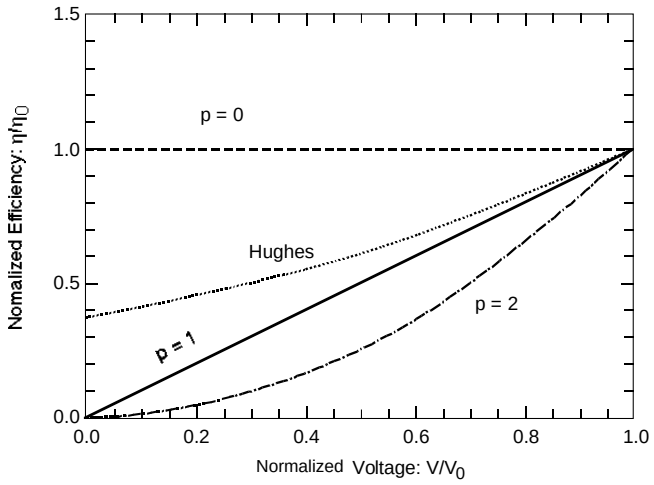

Figure 4. The supply efficiencies assuming $\eta_{inj}(E) = 1$, for some imaginary photoconductors. The abscissa is the normalized potential V/V_0, and the ordinate is the normalized supply efficiency $\eta(V)/\eta_0$: (1) The dashed line corresponds to a photoconductor that has a supply efficiency of unity in the emission-limited situation (and is independent of electric field); (2) the dotted line corresponds to a photoconductor exposed to a flash of short duration and high field photogeneration, followed by Langevin recombination analysis as carried out by Hughes (Ref. 9). This analysis is independent of the field dependence of supply efficiency in the emission-limited case (the high field photogeneration results in a supply efficiency shown by the dashed line); (3) the solid line corresponds to a photoconductor with supply efficiency that increases linearly with field in the emission-limited case. It also represents all photoconductors with high field photogeneration followed by Langevin recombination analysis carried out by Fox (Ref. 13) and Chen (Ref. 14); and (4) the dot–dash curve represents a supply efficiency with a quadratic field dependence under emission-limited conditions.

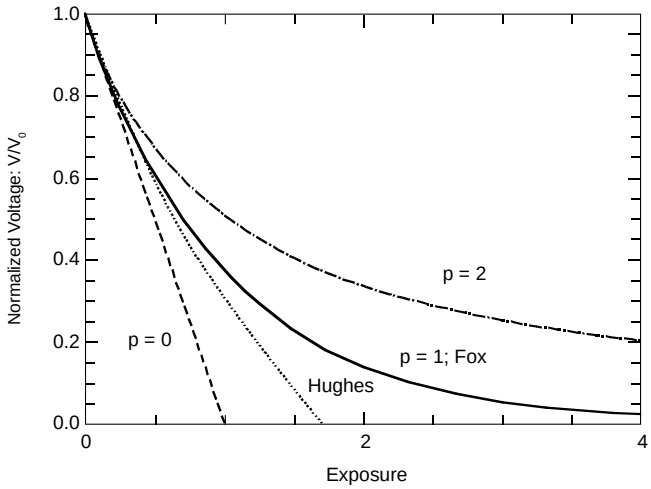

Figure 5. The PIDCs corresponding to supply efficiencies of Fig. 4. The solid line, $p = 1$, is a universal (for low-intensity, emission-limited, as well as high-intensity flash with high field generation) PIDC curve for all photoconductors with high field photogeneration followed by Langevin recombination (Eq. 21). The dashed and dot–dash lines, $p = 0$ and $p = 2$, respectively, represent emission-limited cases. The dotted line represents the high-intensity case as analyzed by Hughes (Eq. 22).

corresponding to total discharge), and the ordinate is the normalized supply efficiency $\eta(V)/\eta_0$. The dashed curve assumes field-independent photogeneration (injection is also assumed to be independent of field), as measured under emission-limited conditions, and represents the $p = 0$ case of Eq. 24. The solid line represents both linear field dependence ($p = 1$) under emission-limited condition and the Fox–Chen result for high field photogeneration followed by Langevin recombination. The dot–dash curve represents quadratic field dependence ($p = 2$) under emission-limited conditions. The dotted line represents Hughes' analysis of high field photogeneration followed by Langevin recombination (Eq. 28). In a previous publication,[16] an error had been made in calculating this efficiency. Hughes' expressions are not valid for our analysis, as Q_{gen} is usually greater than Q_0 (i.e., $f > 1$) for digital xerography, which is our object of interest. However, we display Hughes' results for comparison with those of Fox and Chen, as well as with the emission-limited case. Note, in particular, the discrepancy between the supply efficiencies of the two Langevin recombination models (Eq. 28), even though the difference in the fraction of the generated charge that survives recombination is small for $f << 1$.

The PIDC curves corresponding to the supply efficiencies in Fig. 4 are plotted in Fig. 5. The straight-line PIDC, given by Eq. 25 with $p = 0$, corresponds to the dashed line of Fig. 4. The solid curve is the emission-limited PIDC with linear field dependence ($p = 1$ in the case of Eq. 25) and the Fox–Chen PIDC with high field generation followed by Langevin recombination as given in Eq. 21. The $p = 2$ emission-limited case is shown by the dot–dash line. Also shown is Hughes' PIDC given by Eq. 22. Thus if one goes from the small-signal, emission-limited experiment to a high-intensity flash exposure one should see a dramatic change in the PIDC curve shape if the latter experiment is correctly described by the Langevin recombination model, with the $p = 1$ case being an exception. As seen from Fig. 5, if $p < 1$ (field dependence is sublinear), the PIDC is severely slowed down on going from emission-limited to laser exposures. On the other hand, if $p > 1$ (field dependence is superlinear), the PIDC is *speeded up* on going from the small signal to flash exposures. Because the Langevin model gives a universal PIDC, valid for all photoconductors where the above criteria hold, this reciprocity failure can be used as a tool to test whether Langevin recombination is indeed occurring after flash exposure. This is true even in the case of $p = 1$, except that in this case the occurrence of Langevin recombination is signaled by the *absence* of reciprocity failure.

The discussion thus far did not consider whether the assumptions underlying Langevin recombination are valid in many of the photoconductors employed in electrophotography. Langevin recombination is certainly not applicable in photoconductors employing extrinsic pigments. Extrinsic pigments are those in which excitons migrate to the pigment surface, where an electron transfer from the transport molecule results in hole generation and injection. In these systems holes and electrons exist in different media and do not drift past each other. It is not clear whether the assumption underlying Langevin recombination is valid even in the case of intrinsic pigments, in which electrons and holes do drift past each other within pigment particles. One of the requirements is that the mean free path be much smaller than r_c. For a material of dielectric constant 4.2, r_c is approximately 130 Å. In the crystalline pigments employed in electrophotography, the mean free path may be comparable to or larger than r_c. Thomson recombination may be more appropriate in these cases.[17] The Thomson recombination model applies to dilute systems in which the mean free path between collisions is much larger than the size of the particles (diameter

of cross section). In contrast, the Langevin recombination applies to dense systems in which the number of collisions experienced while diffusing through a length corresponding to a Coulomb radius is large.

Lateral Spread of Raster Output Scanner (ROS) Generated Charge Pattern

Another consequence of exposure to a high-intensity laser beam results from space-charge-limited transport.[7,8] With analog systems employing low-intensity exposure, the exposure time can be much larger than the transit times across the transport layer. The charge carriers in transit in the transport layer at any time provide a small fraction of the charge on the surface of the photoconductor. In digital electrophotography, on the other hand, the entire packet of charge corresponding to a pixel is created in a much shorter time than the transit times. With hole mobilities in the range of 10^{-6} and 10^{-5} cm^2/V-s, the transit time across a photoconductor of 25-μm thickness is in the range of milliseconds to tens of milliseconds. These times are much longer than the exposure times of tens of nanoseconds. The packet of charge while in transit spreads in both the direction of motion and the lateral direction. In the direction of the applied electric field, the spread results from two causes: (1) the leading and trailing fronts of the packet see different fields and hence travel at different speeds[15] (which occurs even if the initial distribution is infinitely thin)[15] and (2) the well-known charge spreading due to dispersive transport observed in all organic disordered systems. The dispersion in the lateral direction is mainly due to Coulomb repulsion, and it is this spread that results in resolution loss.

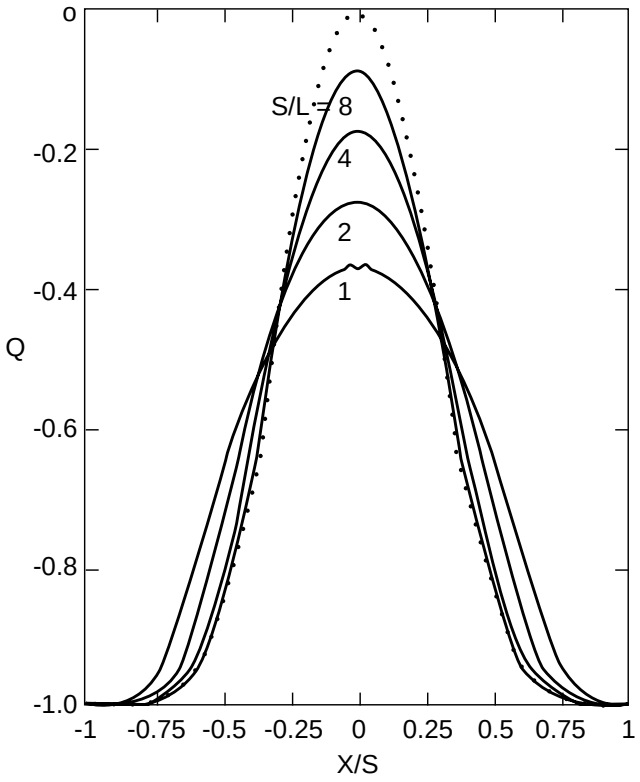

Figure 6. Surface charge pattern resulting from exposure of a photoconductor of thickness L to a 1-D Gaussian charge pattern of width S. The dotted curve is the idealized case without any lateral charge spread. The spread in the charge pattern is shown for four values of S/L. X/S is the distance from the center of the Gaussian as a fraction of S. (From Ref. 7.)

Figure 6 shows the nature and extent of this lateral spread resulting from a 1-D Gaussian charge pattern injected into the photoconductor. The pixel size S is $1/e^2$ width of the Gaussian packet and L is the thickness of the photoconductor. The dotted curve in Fig. 6 represents the case in which carriers move without any lateral dispersion, and it therefore represents an idealized case[7] in which the final discharged surface charge profile is the same as that of the injected profile. Figure 6 also shows the shape of the surface charge distribution for four values of S/L. The charge pattern spread increases as the pixel size decreases or the photoconductor thickness increases, and the final surface charge density is not exactly Gaussian, i.e., the electrostatic image profile is not identical to the optical profile. For typical values of the pixel and photoreceptor thicknesses, this spread can result in as much as a 20 to 40% increase in the pixel width. The distortion of the optical profile can affect the image quality in high-quality digital color xerography.

An attempt has been made to verify this phenomenon experimentally by employing a high-resolution probe.[18] Figure 7 shows the charge profile at the edge of an exposed region where there was a very abrupt edge between the exposed (right side) and the unexposed regions. The authors ascribe a significant portion of this spread to lateral spreading due to Coulomb repulsion effects. Lateral charge drift has also been measured with split electrodes.[19]

In Ref. 7, the distortion of the optical image profile is entirely due to the differential spreading of the packet while in transit. Recent work[8] that includes the generation of the charge via a PIDC curve shows that the charge generation step in itself produces considerable distortion of the optical image. Whenever the PIDC curve is not a straight line (due to a field-dependent supply efficiency, Langevin recombination, or other effects), the discharge is not proportional to exposure (see Fig. 5). Thus, in practical photoconductors, twice the amount of light produces less than twice as much discharge. As a result of this nonlinearity, the generated charge profile is not simply proportional to the exposure profile. The simulations described in Ref. 8 quantify these qualitative arguments and show that the field dependence of the supply efficiency alone can cause considerable distortion in the electrostatic image profile vis-a-vis the optical exposure profile. Thus the *shape* of the PIDC curve is an important factor, even in digital electrophotography.

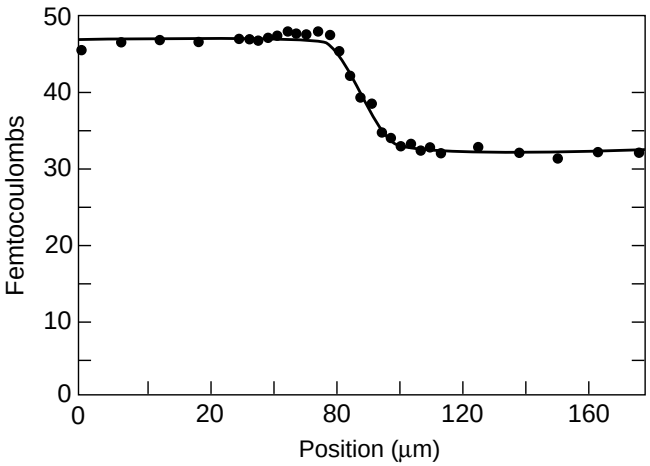

Figure 7. A typical charge profile at the edge of an exposed region of a photoconductor. (From Ref. 18.)

Conclusions

We have discussed two of the myriad effects when an image is created by sequentially exposing a charged photoconductor to a light beam of high intensity and short duration. The first effect deals with increase or decrease of supply efficiency (reciprocity). The second effect deals with the size and shape dilation and distortion of the optical image due to the nature of the creation and transport of a packet of charge. As regards reciprocity, it appears that if the carriers are created at high field followed by recombination, as per the theory of Langevin recombination, all photoconductors should have a universal PIDC curve shape in the absence of any further loss due to injection from the generator layer into the transport layer. This universal shape is one in which the potential goes down exponentially with the photon flux, equivalent to that observed for a photoconductor with a linear field dependence of supply efficiency and operated under emission-limited conditions. Photoconductors with supply efficiency electric field dependence less than one in the emission-limited case will become less sensitive under digital exposure conditions. Photoconductors with supply emission electric field dependence steeper than linear in the emission-limited case will become more sensitive under digital exposure conditions. The assumptions underlying the derivation of the Langevin recombination may not be valid for the crystalline pigments employed in the layered organic photoconductors. Even otherwise, Langevin recombination may not exist in devices employing extrinsic pigments in which the electrons and holes exist in different media. Should such devices show an increase in efficiency in digital mode due to high field photogeneration effects? Taking for granted that the assumptions for Langevin recombination are valid for hydrogenated amorphous silicon (which has a field-independent supply efficiency under emission limited conditions[20]), should one observe an exponential discharge shape in the digital mode? ◬

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