General Model of Sphere-Sphere Insulator Contact Electrification

G. S. P. Castle
Faculty of Engineering Science
University of Western Ontario, London, Ontario, Canada
*L. B. Schein**
IBM Research Division, Almaden Research Center, San Jose, California

Abstract

A general surface state model for sphere-sphere contact charging is suggested from which the familiar low and high density limits are derived. Such a model is applicable to electrophotographic toner-carrier charging experiments. The model is tested against an extended set of toner-carrier charging data gathered from the literature covering a wide range of material properties. In addition, data are reported for the special case of conductive carrier and insulating negative charging toner. These results show that the majority of the data agree with the high density limit of the model.

Introduction

In previous publications, Schein, *et al*[1] pointed out that it is possible to distinguish between the low density and high density surface state theories of contact charging by observing the behaviour of toner-carrier charging as the toner concentration C_t is changed. More specifically, they showed that in a plot of toner mass-to-charge ratio M/Q versus C_t, the universally observed linear relationship has different characteristics for each theory. In the case of the low density limit, the slope to intercept ratio S/I is given as:

$$\frac{S}{I} = \frac{N_t}{N_c}\ \frac{R\rho_c}{r\rho_t} \tag{1}$$

where N_t and N_c are the number of surface states per unit area per unit energy on the toner and carrier respectively, R is the carrier radius, ρ_c the carrier density, r the toner radius and ρ_t the toner density. Here it can be seen that the value of S/I depends both upon geometric properties ($R\rho_c/r\rho_t$) and material properties (N_t/N_c).

In the high density limit case, the value of S/I is given simply as ($R\rho_c/r\rho_t$) thus predicting that S/I is independent of material properties. Using this fact and several sets of data, Schein *et al.* argued that only the high density limit theory agreed with the experimental data. In arriving at these results, the two expressions for the limits were derived by extending a model of the surface state theory of planar contact of two insulators for each case in turn.

In this extension to the previous work, three contributions are offered. The first is a more general analysis of the surface state model for the specific case of sphere-sphere contact charging. From this result, the familiar low and high density limits may be derived as special cases. Secondly, this general model is tested against an extensive set of toner-carrier charging data published in the literature by seven independent workers. These data cover sixty-six sets of toner and carrier diameters and material properties. Finally, the results of an experiment are reported for the special case of conductive carrier and negative charging insulating toner. This is of interest because the conductive carrier presents essentially an infinite supply of negative charges suggesting an infinite value of the surface state density for the carrier. Also, it has a clearly identifiable Fermi level, in contrast to the concept of "effective work function" which is necessary to espouse for insulators.

Theory

The equations for defining the macroscopic relationships for the charging of spherical toners in contact with a spherical carrier can be written with reference to Fig. la. The condition of charge neutrality in the bulk developer results in

$$|Q_c| = |\eta_o Q| \tag{2}$$

where Q_c is the charge on the carrier, η_o the number of toners on the carrier and Q the charge on each toner. Assuming uniform charge distribution on the spherical surfaces, the surface charge density for the carrier and toner can be written as

$$\sigma_c = \frac{Q_c}{4\pi R^2}$$
$$\sigma_t = \frac{Q}{4\pi r^2} \tag{3}$$

Finally, the approximate value of electric field at the contact point between a toner and the carrier particle can be written using superposition as

$$E \doteq \frac{1}{4\pi\varepsilon_o}\left[\frac{Q_c}{R^2} + \frac{Q}{r^2}\right] \tag{4}$$

(Note that this expression ignores the effect of image charges and the dielectric properties of the particles. In a recent publication,[2] Gutmann and Hartmann included these effects and found that expression (4) is accurate within a factor of two for all cases of practical interest.)

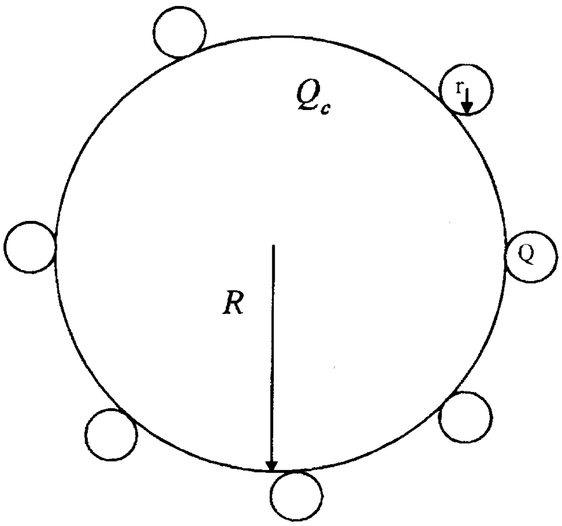

Figure 1a. Macroscopic View of Toner-Carrier Contact

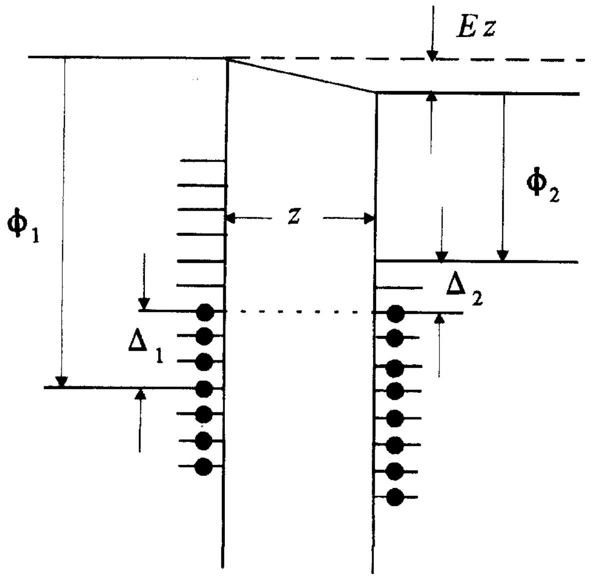

Figure 1b. Microscopic View of Toner-Carrier Contact

Referring to the energy level diagram of Fig. 1b, the equations describing the microscopic conditions resulting from charge transfer may be written. Here the surface charge densites can be expressed in terms of the density of surface states and the changes in effective work functions D1 and D2 due to the charge exchange as

$$\begin{aligned}\sigma_c &= e\Delta_1 N_c \\ \sigma_t &= e\Delta_2 N_t\end{aligned} \tag{5}$$

where e is the value of electronic charge. Finally, the expression for the electric field that exists between a toner and carrier at a tunnelling separation distance z is given by equating the Fermi level energies as

$$\begin{aligned}&\phi_1 - \Delta_1 = \phi_2 + \Delta_2 + eEz \\ &ie.:\ E = \frac{\Delta\phi - (\Delta_1 + \Delta_2)}{ez} \\ &\text{where} \\ &\phi_1 - \phi_2 = \Delta\phi\end{aligned} \tag{6}$$

Combining equations (2), (4), (5) and (6) it can be easily shown

$$\frac{M}{Q} = \frac{\left[\frac{1}{eN_c} + \frac{ez}{\varepsilon_o}\right] C_t R\rho_c + \left[\frac{1}{eN_1} + \frac{ez}{\varepsilon_o}\right] r\rho_t}{z\Delta\phi} \tag{7}$$

This equation describes a linear relation between the mass-to-charge ratio M/Q and the toner concentration C_t. Thus the slope to intercept ratio S/I for this curve is given by

$$\frac{S}{I} = \frac{\left[\frac{1}{eN_c} + \frac{ez}{\varepsilon_o}\right] R\rho_c}{\left[\frac{1}{eN_t} + \frac{ez}{\varepsilon_o}\right] r\rho_c} \tag{8}$$

There are two limits for this relationship which can be identified as being the same as the high and low surface state density limits previously defined by Schein, *et al* [1]. In one extreme, ($1/eN << ez/\varepsilon_0$), we get the high density limit

$$\frac{S}{I} = \frac{R\rho_c}{r\rho_c} \tag{9}$$

whereas the other extreme ($1/eN >> ez/\varepsilon_0$) produces the low density limit defined previously in equation (1). This analysis produces one other possibility, that of an intermediate condition (equation 8) where both factors in the bracketed terms may be important.

Comparison of Results

A number of workers have made measurements on the charge-to-mass ration of toner-carrier mixtures including Kondo,[3] Lee,[4] Wu,[5] Guistina *et al.,*[6] Anderson,[7] Nash & Bickmore,[8] Gutman & Hartmann,[2] Schein *et al*[1] and Andersen.[9]

In all these results, comprising sixty-six experiments carried out on different materials with different toner and carrier diameters at different times and in different laboratories, a linear relationship is found to exist between M/Q and C_t. For each of these published curves, values of the slope and intercept were determined from the data. This value of S/I is referred to as the measured value. In addition, the reported values of toner and carrier radii along with their densities were used to calculate the expected value of S/I using the high density limit defined in equation (9). These are referred to as the calculated values. These data are graphed in Fig. 2. The three lines shown in this Figure represent exact correspondence (the middle line) and correspondence of plus or minus a factor of two. Experimental error of a factor of two is not unreasonable in these experiments given 1) the error bars in measuring Q and M, 2) the possibility that in some of these data sets the toner charge is not saturated, 3) correction factors due to dielectric properties[2] are ignored and 4) the different experimental techniques used by the various workers for measuring Q/M.

The results show that with the exception of some data at very low values of S/I, correspondence between measured and calculated values within the factor of two are obtained. This suggests that the high density limit of the surface state theory satisfactorily predicts the toner charge. On closer examination however, it is clear that although the factor of two agreement is obtained, the majority of the experimental data lies between the upper and exact correlation lines suggesting a trend of the theory to slightly underpredict the toner charge.

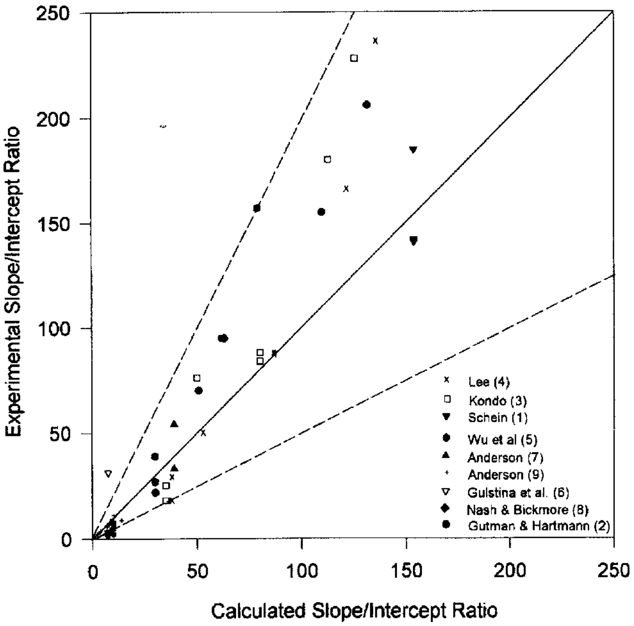

Figure 2. Comparison of experimental and calculated values of S/I

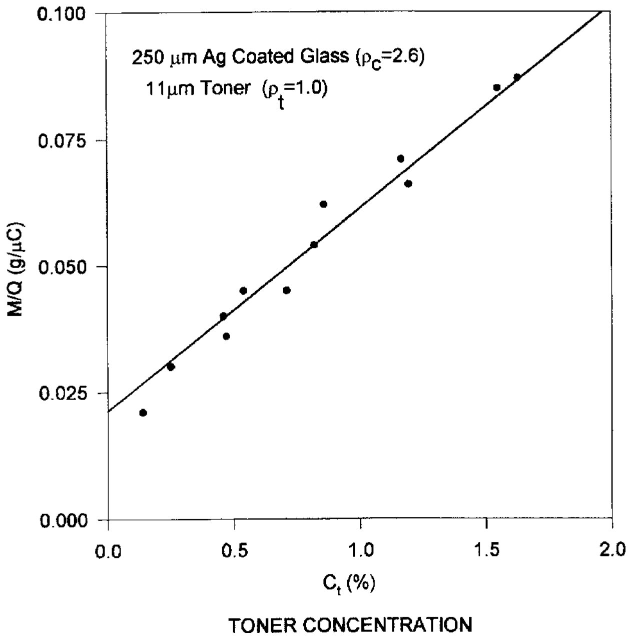

Figure 3. M/Q versus C_t for Conductive Carrier and Insulating Toner

Experiments with Conductive Carrier

As further confirmation of the high density limit, a series of experiments was carried out using conductive silver coated glass carrier of 250μm diameter and standard 11μm diameter toner (IBM Series III). These experiments were carried out under controlled conditions of relative humidity and the toner Q/M measured using the standard cage blow off technique. The results of these experiments are shown in Fig. 3 and indicate a linear relationship between M/Q and C_t. Note that for conductive toner, N_c is expected to be very large (approaching infinity) and equation (1) would predict a linear curve with a slope approaching zero (ie.: S/I → 0). In fact the measured value of S/I from this curve is 170; this compares to the value of 60 as calculated from equation (9), the high density limit. Here the experimental value is once again higher than the calculated and by a factor slightly greater than the factor of two previously observed.

Conclusions

A general expression has been derived which describes both the low density and high density surface state models for sphere-sphere contact charging. From this the low and high density models can be derived as special cases.

By comparison of the predicted values of S/I with an extensive range of published data, it is shown that the high density limit agrees with the majority of the published data, including the special case of conductive carrier. A consistent tendency for the predicted values to slightly underestimate the experimental values of S/I is observed. Possible reasons for this underestimation include the four factors mentioned eailer in the Comparison of Results as well as the neccssity to consider the effect of both bracketed terms in equation (8), a difficult task since there are no measured estimates for N. This analysis suggests that the charge transfer is not limited by the presence of finite surface states on the insulator surfaces (low density limit) but primarily by the electric field generated by the charge transfer at the point of contact.

Acknowledgement

The authors acknowledge with thanks preprints and data supplied by J. Anderson who has analyzed an extensive data base for comparison with the high density limit of the theory. Thanks are also extended to Lexmark International Inc. who partially sponsored this project.

References

1. L.B. Schein, M. LaHa and D. Novotny, *Physics Letters A*, **167**, 1992, p.79; L.B. Schein, *J. Imag. Sci. and Technol.*, **37**, 1993, p.1
2. E.J. Gutmann and G.C. Hartmann, *J. Imag. Sci. and Technol.*, **36**, 1992, p. 335
3. A. Kondo, *Denshi Syasin Gokkoi*, **43**, 1979, p. 26
4. L.-H. Lee, *Photogr. Sci. Eng.*, **22**, 1978, p. 228
5. M.-C. Wu, K.-M. Lui and H.-C. Wang, *Proc. 9th Int. Cong. on Adv. in NIP/Hardcopy '93,* Yokohama, 1993, p. 57
6. R.A. Guistana, J.H. Anderson and D.E. Bugner, *J. Imag.Sci. and Technol.*, **37**, 1993, p. 439
7. J.H. Anderson, *J. Imag. Sci. and Technol.*, **33**, 1989, p. 200
8. R.J. Nash and J.T. Bickmore, *Proc. 9th Int. Cong. on Adv. in NIP/Hardcopy '93*, Yokohama, 1993, p. 68
9. J.H. Anderson, "A Comparison of Experimental Data and Model Predictions for Tribocharging of Two-Component Electrophotographic Developers" submitted *J. Imag. Sci. and Technol.*, 1994

* Current Address: 7026 Calcaterra Dr., San Jose, CA 95120