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Dr. Paul M. Borsenberger (1935-1998)— A Research Retrospective

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Abstract

This paper is a retrospective on the career and research accomplishments of the late Dr. Paul M. Borsenberger. A Senior Research Associate in the Eastman Kodak Company, Paul was internationally renowned for his accomplishments in electrophotographic photoreceptor technology and research on charge generation and transport in amorphous systems. With his passing on July 17, 1998, we lost a colleague and a friend. In this paper we summarize his major research accomplishments and provide guidance for those wishing to review his scientific output of over 140 research publications.

Dr. Paul M. Borsenberger

Originally from St. Louis, Missouri, Paul received a B.S. in Metallurgy from the Missouri School of Mines and Metallurgy in 1960. He served in the U.S. Army for three years and then attended Stanford University where he received the M.S. degree in 1965 and a Ph.D. in 1967, both in Materials Science. While at Stanford he was a Sloan Fellow. His Ph.D. dissertation "Self Diffusion in Cadmium Selenide and Cadmium Telluride" was concerned with the photoconductivity and defect chemistry of compound semiconductors. In 1967 he joined the Research Laboratories of Eastman Kodak Company, Rochester, New York, where he was a Senior Research Associate. His expertise was in the science and technologies related to the photoelectronic properties of solids, and the fabrication and fundamental understanding of the physics of photoreceptors for electrophotographic and other applications. He was a frequent participant and a highly regarded speaker at scientific meetings and symposia. Paul was an author on over 140 research publications in areas related to the photoelectronic properties of solids and the application of these materials to electrophotography. He also co-authored two books, *Organic Photoreceptors for Imaging Systems* (1993, Marcel Dekker, Inc.) and *Organic Photoreceptors for Xerography* (1998, Marcel Dekker, Inc.) and several review articles. Noteworthy review articles are: "Photoconductive Properties of Organic Assemblies and a Comparison with Dark conductors",[1] "Photoreceptors: Organic Photoconductors",[2] "The Role of Disorder on Charge Transport in Molecularly Doped Polymers and Related Materials",[3] and "Disorder in Charge Transport in Doped Polymers".[4] Based on the number of citations received, his 1995 research was cited by the Institute for Scientific Information in *Science Watch* in its roundup of the top ten "hot papers and scientists".

As a tribute to his scientific and technical contributions an SPIE (Society of Photo-Optical Instrumentation Engineers) Proceedings and an issue of the Journal of Imaging Science and Technology have been dedicated to Paul: Proceedings SPIE Vol. 3471, *Xerographic Photoreceptors and Organic Photorefractive Materials IV*, July 22-23, 1998, San Diego, CA; and J. Imaging Sci. Technol. **43** (3 and 5), 1999. In July, 1999, the Symposium on Photoinduced Charge Transfer at the NSF Center for Photoinduced Charge Transfer at the University of Rochester included a paper in tribute to Paul.[5] This presentation is based on that tribute.

Research Publications

Paul's papers include some 48 co-authors. His collaboration with H. Bässler and co-workers at Philipps Universität, Marburg, Germany, began in 1990 and resulted in twenty publications. Paul co-directed the research of a doctoral student, S. Heun, from Bässler's group.[6] Collaborations with F. C. De Schryver and M. Van der Auweraer and co-workers at Katholieke Universiteit Leuven, Heverlee, Belgium, began in 1993 and resulted in nine papers. At the University of Rochester, NSF Center for Photoinduced Charge Transfer, Paul's collaboration with S. Jenekhe resulted in twelve papers, all involving the research of a Postdoctoral Fellow, L.-B. Lin, who carried out the research in Paul's laboratory at the Eastman Kodak Company. Lin is co-author on sixteen papers with Paul.

Paul's research publications can be broadly divided into carrier generation and carrier transport. Much of the

carrier generation research was carried out before 1990 and included papers on the Kodak dye-polymer aggregate material,[7,8] as well as molecularly doped polymers[9,10] These subjects were recently revisited,[11,12] along with the investigation of photoreceptors with generation layers comprised of a near-infrared sensitive phthalocyanine.[13] The carrier transport papers focused on transport models and simulations as well as experimental results. This subject had by far the largest number of papers and represents a substantial contribution to our current understanding of charge transport in disordered materials. The mobilities of over forty hole transport materials were investigated as a function of field, temperature, and concentration as amorphous films or in a variety of polymeric binders. More recent work included the effects of polar additives and the presence of carrier traps. There are a few papers on the electron and bipolar transport characteristics of nine materials as amorphous films and in polymeric binders. Finally, several papers deal with charge transport models and simulations. Listings of these papers according to subject are available.[5]

Charge Transport in Disordered Materials

Most of the Borsenberger publications deal with charge transport in disordered materials. The standard time-of-flight technique was utilized. Mobility is calculated from the transit time and sample thickness as, $\mu = L^2/t_0 V$, where L is the sample thickness, t_0 the transit time, and V the applied voltage. Paul's research was distinguished by the large number of transport materials investigated and the wide range of conditions (binder, concentration, field, and temperature) utilized.

Papers published in 1990 described the transport characteristics of hole and electron transport materials.[14-17] The experimental results were found to be in qualitative agreement with the predictions of the disorder formalism as proposed by Bässler and co-workers.[18-21] In 1991 papers were published in which the experimental results for hole transport were analyzed according to the models and simulations of the Bässler group.[22-25] In these papers the transport characteristics were explained in terms of the disorder formalism in which transport occurs by hopping in a manifold of states subject to energetic and positional disorder. The fundamental equation describing the dependence of the carrier mobility (μ), on temperature (T), and field (E) in terms of two disorder parameters σ and Σ is shown in Eq. 1.

$$\mu(\sigma,\Sigma) = \mu_{00} \exp\left[-\left(\frac{2\sigma}{3kT}\right)^2\right] \exp\left\{E^{1/2}C\left[\left(\frac{\sigma}{kT}\right)^2 - \Sigma^2\right]\right\} \quad (1)$$

The parameter σ describes the width of the Gaussian density of states (energetic or diagonal disorder) in which the transport occurs. The parameter Σ describes the distribution of wavefunction overlap between neighboring transport molecules (positional or off-diagonal disorder). C is an empirical constant, μ_{00} is the mobility at zero field and infinite absolute temperature, and k is the Boltzmann constant. This equation holds for $\Sigma \geq 1.5$. For $\Sigma < 1.5$, Σ^2 in Eq. 1 is replaced by 2.25. Thus, the temperature dependence of the mobility for many transport materials follows the prediction of $\exp-(T_0/T^2)$ as opposed to an Arrhenius type dependence. This difference could only be distinguished when the experiment was carried out over a very wide temperature range. The field dependence of the mobility followed $\exp(\beta E^{1/2})$ where β is proportional to T^{-2}. The temporal features of the mobility, and the nondispersive to dispersive transport transition, are described by the disorder formalism. Lastly, the concentration dependence of the mobility could not be explained by percolation theories. This research was fortified with thorough studies of the mobility characteristics of many different hole and electron transport materials, as neat films or doped into various polymeric binders, as a function of field, temperature, and concentration. Thus, from an analysis of the experimental results the energetic disorder (σ) and positional disorder (Σ) parameters were determined and used to characterize charge transport in the system under investigation. Much of this work is summarized in a review article.[3]

Many studies focused on the causes of mobility differences between transport molecules,[26-32] the effects of polymer binder molecular structure[25,33-35] and the effects of additives.[36] Through these studies it was hypothesized that the static dipole moments within the transport environment, including dipoles present on the transport molecule, give rise to random dipolar fields that affect the energetic disorder and cause an increase in the width of the density of states involved in the charge transport.[37] This hypothesis has been successfully used to rationalize the transport behavior of a large number of both hole and electron transport systems.

In the investigations of some charge transport systems, low concentrations of p-EFTP in bisphenol-A-polycarbonate in particular, it was found that the disorder formalism provided an inadequate description of the experimental observations relating to the field dependence of the mobility.[38] Polaron models were invoked but it was determined that polaron effects could not account for the observed field and temperature dependencies of the mobility.[3,4,39,40] The effects were ascribed to the unusual molecular structure of this particular transport molecule.

Some recent publications described the effects of extrinsic traps on charge transport. In these studies a polymer was doped with a hole transport material along

with a material having a lower oxidation potential such that it would act as a hole trap.[41-44] The transport characteristics were adequately described by the disorder model where the width of the density of states of the transport manifold was replaced by an effective width which depends on the difference in oxidation potentials between the transport material and the trap, and the trap concentration. Similar results in electron transporting systems were published posthumously.[45,46]

Shortly before his death, Paul began a collaboration with A. Kadaschuck and co-workers (National Academy of Sciences of Ukraine, Kiev) using thermally stimulated luminescence to obtain information about energetic disorder in molecularly doped polymer systems.[47-49]

The Contributions of Paul M. Borsenberger

The scientific contributions of Paul M. Borsenberger are in the open literature and will receive the test of time. More importantly, with his passing we lost an enthusiastic colleague and friend. Paul's influence should be judged not only by those papers in which he was an author or co-author, but also by the frequency with which he was cited in the Acknowledgement sections of publications thanking him for suggestions, discussions, generosity, and so on. The personal contributions of someone who has made such an impact on so many of us, in so many ways, are much more difficult to define. Paul meant something different to each of us and we are grateful that he has crossed our paths and made our lives so much richer.

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Biography

David S. Weiss received his B.S. degree in Chemistry from Lehigh University in 1965 and his Ph.D. in Chemistry from Columbia University in 1969. In 1978 he joined the Eastman Kodak Company and is now with Heidelberg Digital L.L.C. His work focuses on electrophotographic technologies with emphasis on organic photoreceptors. Research interests include organic photochemistry and photophysics. He co-authored, with P.M. Borsenberger, *Organic Photoreceptors for Imaging Systems* (Marcel Dekker, Inc., 1993) and *Organic Photoreceptors for Xerography* (Marcel Dekker, Inc., 1998). He is co-editor, with A. S. Diamond, of the soon to be published *Handbook of Imaging Materials, Second Edition* (Marcel Dekker, Inc.). He has been an Associate Editor of the Journal of Imaging Science and Technology since 1988. In 1999 he received the Carlson Memorial Award from the IS&T. A long time member of the American Chemical Society he served as the Chair of the Rochester Section of the ACS in 1997 and in 2000 he received the Rochester Section ACS Award.
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