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MEASURED BEHAVIOR OF GAMMA-RAY PHOTOCONDUCTIVITY IN ORGANIC DIELECTRICS

by

S. E. Harrison

June 1962

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ABSTRACT

Photoconductivity measurements are reported for polyethylene, polystyrene, a mica-filled epoxy formulation, polypropylene, nylon, Teflon, diallylphthalate, and H-film. The measurements were made at gamma-ray intensities within the interval from 1.0×10^{-3} rads(H_2O)/sec to 1.0×10^4 rads(H_2O)/sec and at temperatures which ranged from 38°C to 71°C . Conductivity was found to have distinct features in three time intervals denoted as A, B, and C. In interval A conductivity is responding to a step increase in gamma-ray intensity. This response is exponential in nature with the time constant decreasing with increased gamma-ray intensity. The change in time constant (τ_o) as a function of gamma-ray intensity ($\dot{\gamma}$) at a fixed temperature is approximated by

$$\tau_o = B\dot{\gamma}^{-\mu}$$

where B and μ are empirical constants. In interval B the photoconductivity ($\sigma - \sigma_o$) has reached an equilibrium value whose magnitude as a function of gamma-ray intensity at a fixed temperature is characterized to good approximation by

$$(\sigma - \sigma_o) = A\dot{\gamma}^\delta$$

where A and δ are empirical constants. In interval C the conductivity is recovering upon sample removal from the gamma-ray environment. The measured photoconductivity decay can be characterized by

$$\sigma = \sigma_{eq} \sum_{i=1}^n A_i e^{-t/\tau_i}$$

where σ_{eq} is the equilibrium conductivity of interval B defined by $\sigma_{eq} = \sigma_o + A\dot{\gamma}^\delta$, the τ_i 's are discrete decay time constants of the recovery, the coefficients, A_i , are the weighting factors associated with the i^{th} decay time constant, and n is the number of discrete decay time constants in the recovery process.

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MEASURED BEHAVIOR OF GAMMA-RAY PHOTOCONDUCTIVITY IN ORGANIC DIELECTRICS

Introduction

The photoconductivities of eight organic dielectric materials exposed to gamma-radiation were measured at intensities in the range of 1.0×10^{-3} rads*(H₂O)/sec to 1.0×10^4 rads(H₂O)/sec. The source of gamma-radiation was the fission product inventory of Engineering Test Reactor (ETR) fuel elements. Measurements of the photoconductivity properties of polyethylene, polystyrene, a mica-filled epoxy formulation, polypropylene, nylon, Teflon, diallylphthalate, and H-film were made at controlled temperatures.

The photoconductivity properties of extremely low conductivity ($< 10^{-15}$ ohm⁻¹cm⁻¹) organic dielectric materials constitute a relatively unexplored, unresolved field. Basic investigations of the photoconductivity mechanisms have been restricted largely to single crystal, high purity inorganic materials. The photoconductivities of organic polymers reveal a quantitative behavior similar in form to that of the photoconductivities of inorganic crystalline structures and suggest the conclusion that the fundamental processes in both material types are in a general way related. The most distinctive structural difference between inorganic crystals and organic polymers is the amorphous and semicrystalline nature of the latter. Semicrystalline materials are those which have crystalline regions formed interspersed in the amorphous mass of the polymer chain. According to recent theoretical work by Lauritzen and Hoffman¹, the organic crystalline unit cells are formed by chain folding, i. e., such crystalline regions consist of uniform lamellae with the organic molecules approximately normal to the plane of the lamellae in a sharply, regularly folded configuration.

Basically, the photoconductivity processes involve the absorption of energy from radiation, the excitation of charge carriers from nonconducting states to conducting states, and the return of charge carriers from conducting states to nonconducting states. There are three principal mechanisms by which gamma-rays interact with matter to produce photoconductivity. These mechanisms are photoelectric effect, Compton effect, and pair production, which are discussed in many texts.² The photon-electron interactions produce ions, free electrons, and excited atoms or molecules. Ionization results when the incident photon removes an electron from its parent atom or molecule leaving an electron deficiency, i. e., a hole associated with an atom or molecule. The ionized electrons may have sufficient kinetic energy to cause secondary ionization and excitation in neighboring atoms where, upon subsequent collisions, they become sufficiently nonenergetic to become captured by the same or other atomic nuclei. The term "excitation" refers to a process by which

*Rad(H₂O) = 100 ergs of energy absorbed per gram of H₂O = 6.24×10^{13} electron volts of energy absorbed per gram of H₂O.

¹Lauritzen, J. I., and Hoffman, J. P., "Theory of Formation of Polymer Crystals with Folded Chains in Dilute Solution," J. Res. N. B. S., 64A, 73 (1960).

²One text is by Price, W. J., "Nuclear Radiation Detection," McGraw-Hill Book Co., Inc., 1958.

an electron is raised to a higher electronic energy level, but the electron remains bound to its parent nucleus. Excitation can result from direct photon-electron interaction or as a secondary process as indicated above. Gamma-ray photons lose the majority of their energy in the interactions just discussed. Seitz and Koehler³ quote a value of 1 percent for the amount of energy lost in other ways. Typical electron transitions in photoconductors are discussed by Bube.⁴

The subject of trapping has a distinct part in explaining the photoconductivity process. Trapping is the spatial confinement of an electron or hole, whereby the electron or hole is prohibited from moving freely through the material unless supplied with additional thermal or photon energy. In accord with photoconductivity terminology, the term "trap" or "trapping" is reserved for centers whose occupancies are dictated by thermal equilibrium exchange with the nearest allowed band, i. e., thermal release of electrons and holes to the conduction and valence bands, respectively. The rate of release depends on temperature according to the relationship $\exp(E/kT)$ where E is the depth of the trap. A material containing large numbers of deep "traps" may show reduced photoconductivity, and a slow decay of this conductivity after removal of the irradiation source as the carriers are slowly released from "traps." Those traps which do not have a significant thermal exchange with the nearest allowed band are called "recombination centers." Because of this definition, there is an inherent vagueness in defining what types of centers are "traps"; in fact, any center can be a "trap" under one condition of incident photon intensity and temperature, and a recombination center under another condition.

This brief discussion draws heavily on current single crystal photoconductivity theory. This is the most logical starting point for photoconductivity work in insulating materials. Polymer-type organic structures are not well defined. Consequently, any basic study of the photoconductivity process in polymeric materials is complicated by the inhomogeneous way in which the polymer chains are intermingled. The electron energy levels are determined by the molecular and intermolecular forces, and the valence electrons that are dealt with are not necessarily associated with a single atom but are molecular valence electrons.⁵

The dependence of photoconductivity ($\sigma - \sigma_0$) on irradiation intensity (γ) at a given temperature in insulating materials can be characterized to good approximation for organic dielectrics by

$$(\sigma - \sigma_0) = A\gamma^\delta \quad (1)$$

where A and δ are empirical constants. Photoconductivity of this form is based on the model of Rose⁶ and has been found by Fowler⁷ and others^{8,9} to exist at low intensities for some organic dielectric materials.

³Seitz, F., and Koehler, J. S., International Conference on Peaceful Uses of Atomic Energy, Geneva, 7, 615 (1955).

⁴Bube, R. H., "Photoconductivity of Solids," John Wiley and Sons, Inc., New York, 1960.

⁵Aftergut, S., and Brown, G. P., General Electric Co., Schenectady, N. Y. Paper given at Conference on Organic Semiconductors, Chicago, April (1961).

⁶Rose, A., "An Outline of Some Photoconductive Processes," RCA Review 12, 363(1951).

⁷Fowler, J. F., "X-ray Induced Conductivity in Insulating Materials," Proceedings of the Royal Society of London, 464 (1956).

⁸Winslow, J. W., "Radiation Induced Currents in Polyethylene," AIEE Conference Paper 60-1156.

⁹Coleman, J. H., 23rd Annual Meeting, Conference on Electrical Insulation, Sponsored by NAS-NRC (1955).

The experimental procedure for this work is described in a previous paper.¹⁰ Consequently, only the salient features of this procedure will be mentioned here. Each sample tested was a circular disc, 10.16 cm in diameter. Sample thicknesses ranged from 0.020 cm to 0.316 cm. Because of the convenience in calculating fringing effects for varying sample thickness, the electrode dimensions were as suggested by ASTM D 257-58. For the measurement of conductivity (see Figure 1), each sample disc, along with electrodes and

(a) Test Configuration

(b) Encapsulated Unit (Material - Epoxy 1478-1)

Figure 1. Test Configuration and Encapsulated Unit

¹⁰ Harrison, S. E., and Snyder, A. W., "Gamma-ray Photoconductivity in Polyethylene, Polystyrene, and an Epoxy Formulation." Conference on Electrical Insulation sponsored by NAS-NRC, Pocono Manor, Pa., Oct. 23-25, 1961 (Sandia Corp. Reprint No. SCR-442).

heating elements, was encapsulated in a thermal-setting resin for the purpose of waterproofing and reduction of ionization leakage currents. The heating elements gave temperature control from 38°C to 71°C. Because of the necessity of shielding the measuring circuit, two coaxial cables were used for monitoring the resistance of each sample disc. The resistance of the sample discs was recorded continuously using a Brown strip-chart recorder driven by either a Megatrometer or by a Tera-ohmmeter. Repeated measurements with the Megatrometer, Tera-ohmmeter, Brown strip-chart recorder, and encapsulated test units revealed a random error of ± 8 percent. With voltage applied, a stabilization time of 1.8×10^3 seconds was observed before data were taken on a given sample.

In all of this work "volume excited currents" are assumed, i. e., free positive and negative charges are uniformly distributed and space charge effects do not occur.

The following parts of this paper, based on empirical data, present and discuss the dependence of photoconductivity on time and gamma-ray intensity at a fixed temperature. The Appendix is included to give a brief description of the material molecular structures, and Table I presents dark conductivity, applied field, thickness, and specific gravity for the eight material types studied.

TABLE I
Dark Conductivity, Applied Field, Thickness, and Specific Gravity for Eight Material Types

Material ^(a)	Dark conductivity ^(b) γ_o (ohm - cm) ⁻¹	Applied field E 10^3 v/cm	Sample thickness t cm	Specific gravity d_4^{20}
Polyethylene	3.2×10^{-19}	6.0	0.083	0.96
Polystyrene	3.0×10^{-19}	3.0	0.084	1.02
Epoxy 1478-1	3.0×10^{-15}	3.1	0.160	1.52
Polypropylene	5.2×10^{-18}	6.7	0.075	0.91
H-film	5.0×10^{-18}	2.4	0.024	1.39
Teflon	8.4×10^{-19}	7.0	0.072	2.15
Nylon	1.3×10^{-15}	3.0	0.083	1.14
Diallylphthalate	4.4×10^{-17}	3.1	0.165	1.65

(a) See the Appendix for a brief description of the material molecular structures.

(b) Data taken at 38°C.

Conductivity Versus Time

The general form of a conductivity versus time curve for organic dielectrics is shown in Figure 2, where the gamma-ray intensity is represented as a rectangular function initiated at time (a) and removed at time (b). The conductivity data have distinct features in three time intervals denoted as A, B, and C.

Figure 2. Typical Behavior of Conductivity in Response to a Rectangular Pulse of Gamma-Ray Intensity

Interval A is the interval of time in which photoconductivity is responding to a step increase in radiation intensity, but the conductivity has not yet achieved equilibrium. Interval B is the interval during which the conductivity has reached an equilibrium value determined for a specific material by the radiation intensity and temperature of the sample of material. Interval C is the interval of recovery of the conductivity upon removal of the sample from the gamma-ray field.

The conductivity in organic dielectric materials as a function of gamma-ray intensity and time (t) at a fixed temperature (T) is presented utilizing the "unit step function," $U(t)$. This unit step function permits

the convenient presentation of conductivity in equation form for the three time intervals mentioned. The generalized expression is

$$\sigma(t, \dot{\gamma}) \Big|_{T = \text{const.}} = U(t)\sigma_1(t) + U(t-a)\left[\sigma_2(t-a, \dot{\gamma}) - \sigma_1(t)\right] + U(t-b)\left[\sigma_3(t-b) - \sigma_2(t-a, \dot{\gamma})\right] \quad (2)$$

where $\sigma_1(t)$ is the initial dark conductivity of a material, $\sigma_2(t-a, \dot{\gamma})$ is a function which includes the response of interval A and the magnitude of the equilibrium conductivity of interval B, and $\sigma_3(t-b)$ is a function which describes the recovery behavior of interval C. This generalized expression for conductivity has been verified for polyethylene, polystyrene, and a mica-filled epoxy formulation. Additional data indicate that the expression also holds for a large number of organic polymers. Data are presented on polypropylene, nylon, Teflon, diallylphthalate, and H-film.

Conductivity Rise Time

The significant observation associated with interval A of Figure 2 is the time constant, τ_o , with which the rise from the dark conductivity, σ_o , to the plateau of interval B is characterized. This plateau represents an equilibrium condition, a function of intensity and temperature, where the rate of generation of free carriers is equaled by the rate of carrier annihilation through recombination, and the rate of capture of free carriers in trapping (metastable) states is equal to the rate of release from trapping states. The time constant of the rise within interval A indicates a finite time that is associated with this equilibrium plateau, before which the rate of generation of free carriers exceeds the rate of recombination of free carriers. This time constant decreases with increased intensity. Measured data for polyethylene, polystyrene, and Epoxy 1478-1 are presented in Figure 3. A straight line on the $\ln \dot{\gamma}$ versus $\ln \tau_o$ plots of Figure 3 approximates the data points. The line is represented by the mathematical expression

$$\tau_o = B\dot{\gamma}^{-\mu} \quad (3)$$

where B and μ are empirical constants. μ is found to be 0.5 in all three cases, and B is 45, 60, and 135 for polyethylene, polystyrene, and Epoxy 1478-1, respectively, when $\dot{\gamma}$ is expressed in rads (H_2O)/sec and τ_o is expressed in seconds. The time constants at 1.0×10^{-1} rads (H_2O)/sec (taken from the curves) for polyethylene and polystyrene are, respectively, 148 seconds and 182 seconds. Below 1.7 rads (H_2O)/sec, Epoxy 1478-1 does not exhibit a measurable photoconductivity. The time constant at 1.0×10^3 rads (H_2O)/sec (taken from the curves) for polyethylene, polystyrene, and Epoxy 1478-1 are, respectively, 1.6 seconds, 1.9 seconds, and 4.1 seconds.

Conductivity Versus Intensity

The plateaus (interval B of Figure 2) of the continuously measured conductivity time curves are used to obtain photoconductivity-intensity curves with temperature as a controlled variable. Typical photoconductivity-intensity data for Teflon, nylon, and polyethylene are shown in Figure 4. The dependence of photoconductivity ($\sigma - \sigma_o$) on irradiation intensity at a given temperature in all insulating materials studied can be characterized to good approximation by

$$(\sigma - \sigma_o) = A\dot{\gamma}^{\delta} \quad (4)$$

Figure 3. Logarithm of Time Constant Versus Logarithm of Gamma-Ray Intensity for Polyethylene, Polystyrene, and Epoxy 1478-1 at 38°C

where σ is the plateau equilibrium conductivity (σ_{eq}) of interval B, σ_0 is the dark conductivity, and A and δ are empirical constants. A and δ are summarized in Table II for several material types with temperature and intensity as variables. A dependence of photoconductivity of this form is expected from the model of Rose¹¹ and has been found by Fowler¹² at low intensities ($\dot{\gamma} < 1.6$ rads (H_2O)/sec).

The theoretical treatment of Rose predicts a range of value of $0.5 \leq \delta \leq 1.0$. On the basis of the models by Rose, Fowler has shown how values of δ between 0.5 and 1.0 might be obtained for insulating materials (assuming a conventional band structure), considering an exponential distribution ($\delta \rightarrow 0.5$) of trapping levels or a uniform distribution ($\delta \rightarrow 1.0$) of trapping levels below the conduction band.

¹¹Rose, A., (op. cit., Ref. 6).

¹²Fowler, J. F., (op. cit., Ref. 7).

Figure 4. Logarithm of Photoconductivity Versus Logarithm of Gamma-Ray Intensity for Teflon, Nylon, and Polyethylene at 38°C

TABLE II

Measured Values of A and δ for Eight Materials as Defined by $(\sigma - \sigma_0) = A\gamma^\delta$

Material	Temperature °C	δ	A	Range of γ rads (H ₂ O)/sec
Polystyrene	38	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
	49	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
	60	0.97	4.0×10^{-17}	1.7×10^{-2} to 5.0×10^3
Polyethylene	38	0.74	5.2×10^{-16}	8.3×10^{-2} to 1.7×10^3
	49	0.74	6.3×10^{-16}	8.3×10^{-2} to 1.7×10^3
	60	0.74	1.6×10^{-15}	8.3×10^{-2} to 1.7×10^3
Epoxy 1478-1	38	No measurable photoconductivity below $\gamma = 1.7$		
		1.0	3.3×10^{-17}	1.7 to 4.2×10^3
	49	No measurable photoconductivity below $\gamma = 9.0$		
		1.0	3.3×10^{-17}	9.0 to 4.2×10^3
	60	No measurable photoconductivity below $\gamma = 7.5 \times 10^1$		
		1.0	3.3×10^{-17}	7.5×10^1 to 4.2×10^3
Polypropylene	38	0.88	3.8×10^{-17}	1.8×10^{-3} to 6.0×10^3
H-film	38	1.1	5.8×10^{-18}	1.8×10^{-3} to 6.0×10^3
Teflon	38	1.0	1.2×10^{-16}	1.8×10^{-3} to 6.0×10^3
Nylon	38	No measurable photoconductivity below $\gamma = 8.0$		
		1.3	2.8×10^{-18}	8.0 to 6.0×10^3
Diallylphthalate	38	0.30	2.1×10^{-16}	1.8×10^{-3} to 3.0×10^2
		1.7	8.0×10^{-20}	3.0×10^2 to 6.0×10^3

Note: (1) Data taken under steady state conditions after 1.8×10^3 seconds of electrification.

(2) 15 samples of polyethylene, polystyrene, and Epoxy 1478-1 have been measured.
3 samples of the other materials have been measured.

Utilizing from Figure 2 the exponential nature of interval A and the equation for photoconductivity of the plateau region of interval B (Equation 4), the function $\sigma_1(t)$ can be written as

$$\sigma_1(t) = \sigma_o = \text{constant} \quad (5)$$

and the function $\sigma_2(t-a, \dot{\gamma})$ can be written as

$$\sigma_2(t-a, \dot{\gamma}) = \sigma_o + A\dot{\gamma}^\delta - A\dot{\gamma}^\delta e^{-\frac{t-a}{\tau_o(\dot{\gamma})}} \quad (6)$$

where, from Equation 3, $\tau_o(\dot{\gamma}) = B\dot{\gamma}^{-\mu}$.

Conductivity Recovery

Conductivity decays slowly after radiation exposure is abruptly stopped. This slow rate of decay is assumed to be dictated by the effect of trapping. The effect of trapping is to make the measured decay time constant* of the photoconductivity longer than the carrier recombination rate. The measured photoconductivity decay of interval C (Figure 1), taken at one temperature and one gamma-ray intensity, for the organic materials of this work can be characterized as in the following equation by

$$\sigma_3(t-b) = \sigma_{eq} \sum_{i=1}^n A_i e^{-\frac{t-b}{\tau_i}} \quad (7)$$

where σ_{eq} is the equilibrium conductivity of interval B defined by $\sigma_{eq} = \sigma_o + A\dot{\gamma}^\delta$, the τ_i 's are the decay time constants of the recovery, the coefficients A_i are the weighting factors associated with the i^{th} decay time constant, and n is the number of discrete decay time constants in the recovery process. Decay data for polyethylene, polystyrene, and Epoxy 1478-1 after exposure to 1.7×10^3 rads (H_2O)/sec at $54^\circ C$ are presented in Figure 5. For polyethylene, $n = 2$, $\tau_1 = 2.0$ sec, and $\tau_2 = 20$ sec. For Epoxy 1478-1, $n = 1$ and $\tau_1 = 2.2$ sec. Additional decay terms may indeed exist for the epoxy; however, they are insignificant in their contribution to the recovery process. In comparison, polyethylene has much longer time constants, and the shape of the decay curve does not permit the separation of these constants.

Some discussion is warranted as to the relative magnitude of the initial decay constant, τ_1 . It is possible that τ_1 could be attributed to a recombination process; however, the measured time constants are deemed much too long for such a conclusion. The simplest and most general relation characterizing photoconductivity is Rose's equation,¹³

$$n = f\tau \quad (8)$$

* Decay time constant: Time required for conductivity to decay $1/e$ of its initial value.

¹³Rose, A., "Performance of Photoconductors," Photoconductivity Conference, Atlantic City (1954).

Figure 5. Recovery Curves at 54°C After Exposure to 3.3×10^3 Rads (H_2O)/Sec

where n is the steady state increase in the density of free carriers generated by f excitations per second per unit volume and τ is the lifetime of these carriers in the free state. An equation¹⁴ for carrier generation rate per unit volume is

$$f = \frac{K\rho\gamma}{12} \quad (9)$$

¹⁴Harrison, S. E., "A Study of Gamma-Ray Photoconductivity in Organic Dielectric Materials," A Thesis, The Univ. of New Mexico, 1962 (Sandia Corp. Reprint No. SCDC-2580).

where K is a constant which equals 6.24×10^{13} ev/gm-rad, $\dot{\gamma}$ is the intensity in rads (H₂O)/sec, ρ is the material density, and 12 is a constant in ev per hole-electron pair formed. The constant of 12 is taken as a best estimate of the energy required per hole-electron pair formed and is based upon an assumed band gap¹⁵ of 4 ev for insulating materials and Brown's¹⁶ average figure, for silicone, of three times the energy gap for each hole-electron pair formed. Utilizing Equation 8 and for convenience assuming conduction by electrons only, the equation for conductivity gives

$$\sigma = q\mu_n n = q\mu_n \tau f \quad (10)$$

Based on Equations 9 and 10, values of $\mu_n \tau$ were found to be nominally 2.8×10^{-10} cm²/volt for polyethylene, polystyrene, and Epoxy 1478-1 over the gamma-ray intensities of this work. Consequently, it is difficult to conceive of a mobility sufficiently low that τ should have a magnitude of a few seconds, as is the case in Figure 5--thus the conclusion that the τ 's are attributable to trap decay processes which are recognized to be exponential in nature. At this time the state of the art of mobility measurements does not permit the separation of μ and τ in these extremely low conductivity organic dielectric materials.

Summary

This study of gamma-ray photoconductivity in organic dielectric materials has resulted in qualitative observations associated with intervals A, B, C of Figure 2. Interval A is exponential in nature, and the time constant of the response as a function of gamma-ray intensity is characterized by

$$\tau_o = B\dot{\gamma}^{-\mu}$$

The plateau region of interval B is a function of gamma-ray intensity and is characterized by

$$\sigma_{eq} = \sigma_o + A\dot{\gamma}^{\delta}$$

The recovery process of interval C exhibits discrete decay constants, and conductivity decay is approximated by

$$\sigma = \sigma_{eq} \sum_{i=1}^n A_i e^{-\frac{t-b}{\tau_i}}$$

Combining these observations with Equation 2, the generalized equation for conductivity as a function of time and intensity at a fixed temperature, yields the following:

¹⁵Kittel, Charles, Introduction to Solid State Physics, John Wiley and Sons, Inc., 1957.

¹⁶Brown, W. L., "Introduction to Semiconductor Particle Detectors," IRE Transactions on Nuclear Science, 8, 1, January (1961).

$$\sigma(t, \gamma) \Big|_{T = \text{const}} = U(t) \sigma_o + U(t-a) \left\{ \left[\sigma_o + A \gamma^\delta - A \gamma^\delta e^{-\frac{t-a}{\tau_o(\gamma)}} \right] - \sigma_o \right\} + U(t-b) \left\{ \sigma_{eq} \sum_{i=1}^n A_i e^{-\frac{t-b}{\tau_i}} \right.$$

$$\left. - \left[\sigma_o + A \gamma^\delta - A \gamma^\delta e^{-\frac{t-a}{\tau_o(\gamma)}} \right] \right\}$$

This equation can be extended to include the situation where the gamma-ray intensity is shut off at time (b) greater than time (a) and before the conductivity has reached an equilibrium value. Further work on the response characteristics and recovery processes is in progress.

APPENDIX

CHEMICAL STRUCTURE OF SELECTED ORGANIC MATERIALS

This appendix is included to present a brief description of the molecular structure of the materials studied in this photoconductivity work.

Polyethylene

The polyethylene (Marlex 50) polymer is reported to be as high as 60 percent crystalline. This is a linear polymer and is typically represented as

Polystyrene

Polystyrene has a long chain structure with a benzene ring attached as indicated below:

All presently available polystyrene is completely amorphous due to the random stereoisomerism of the structure.

Polypropylene

The basic propylene structure is

Propylene does not polymerize readily. The polypropylene molecule can exist as an atactic (random) polymer, an isotactic (all the substituents lie on one side of a theoretical plane containing the main C-C chain) polymer, or a syndiotactic (the substituents alternate above and below a theoretical plane containing the main C-C chain) polymer. Here the polypropylene molecule is represented as a syndiotactic polymer.

Teflon

Teflon (polytetrafluoroethylene) is a linear saturated fluorocarbon, i. e., linear polyethylene with all hydrogen atoms substituted by fluorine atoms.

Nylon

The nylon used is Zitol 101 (66 nylon) and is formed from the six-carbon acid and six-carbon diamine, adipic acid, and hexamethylene diamine. The structure is as follows:

H-Film

H-film is a new organic film similar in structure to Mylar. Infrared analysis of the H-film indicates polyester groups similar to Mylar but with more phenyl groups than Mylar. The H-film is much superior to Mylar in temperature properties. For comparison purposes, the basic repeat unit for Mylar is

Epoxy 1478-1

This thermalsetting resin is basically Shell Epon 828 with variations in curing agent and filler. The formulation is as follows:

Base Resin: 60 PBW, Shell Epon 828

Filler: 40 PBW, 4x mica

Curing Agent: 7.2 PBW, diethanolamine (DEA)

Curing Time: 15 hours at 74°C

The 4x mica filler is reinforcing

Diallylphthalate

For practical purposes, the percentage of the compounds used in the manufacture of diallylphthalate (50-20-30) are as follows:

Type "E" Glass	30.0 percent
Diallylphthalate	54.0 percent
Kaolinite	14.0 percent
Calcium Stearate	1.0 percent
Tertiary Butyl Perbenzoate	1.0 percent