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U.S. Atomic Energy Commission

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INVESTIGATION OF ENERGY TRANSFER

PROCESSES BY FLASH PHOTOLYSIS

(Radiation Effects in Solids)

by

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January, 1970

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INTRODUCTION

This report summarizes the research progress during the period June 15, 1958 through January 31, 1970. The original objective of this program was to apply the flash photolysis method to energy transfer processes in condensed systems. In flash photolysis the substance of interest is irradiated with a short duration, high intensity light flash, which produces a non-equilibrium yield of the first reaction intermediates. These intermediates are identified by making fast measurements of their optical absorption spectra, while the kinetics of the processes by which the intermediates are formed and disappear can be studied by following the temporal changes in the absorption spectra. The original program involved the investigation of two different types of photochemical systems. One of these studies was based on photochemical reactions in solution sensitized by organic dyes. This work was an extension of the earlier types of flash photolysis investigations on photochemical systems. The second phase of the program involved the application of flash photolysis to studies of color centers in alkali halides. This approach was quite original and eventually led to new information about the light-induced transformations of color centers.

During the course of the project it became apparent that the scope of each aspect was sufficiently broad that independent organization of each would be desirable. Accordingly, the photochemistry studies per se were transferred from this program to a new project supported by the National Institutes of Health in 1962, while the alkali halide studies were expanded

to include mechanical radiation damage effects and dye-sensitization of semiconductors; (The NIH grant is currently active and in its seventh year). The research accomplishments are described in some detail in the actual Progress Reports, No.1 January 1959 through No.9 February 1968 and in journal articles, theses, and meeting papers based on this work. A listing is given in Table III. In view of the available detailed information, this Final Report includes only a brief summary of the major research topics and the most significant results.

RESEARCH RESULTS

A chronological summary of the research topics investigated during the course of this project is given in Table I, accompanied by a listing of the scientific personnel in Table II. In general, the research falls into the following areas:

- A. Dye-sensitized photochemical oxidation of aqueous phenol;
- B. Low-temperature photoequilibria between F and F' centers;
- C. Optical formation of F-aggregate centers and their spin-metastable states;
- D. Effects of radiation on surface properties of alkali halide crystals;
- E. Mechanism of spectral sensitization of zinc oxide photoconductivity.

A brief summary of each project follows:

A. Dye-sensitized Photochemical Oxidation of Aqueous Phenol

Flash photolysis is ideally suited for the study of dye-sensitized photochemical processes because the sensitizer can be irradiated with a visible light flash not absorbed by the substrate and the initial sensitizing intermediates can be investigated by means of their absorption spectra. An early study of this type was undertaken as part of this program and eventually led to a definitive mechanism for the photooxidation of aqueous phenol (Table III - 6,9). It was found that optical excitation of Fluorescein and its halogenated derivatives leads to production of the metastable triplet state which is the sensitizing intermediate. The reaction of the dye-triplet state with phenol causes oxidation of phenol to the phenoxyl radical and reduction of the dye to the unstable semiquinone intermediate. A fast back reaction of the reduced dye and oxidized phenol takes place so that this type of process cannot be observed in conventional photochemical studies. Interestingly, the ultraviolet flash photolysis of aqueous phenol produces the same phenoxyl radical primary product. This work led to the spectra of the various intermediates, their extinction coefficients, and rate constants for the predominant reactions. The extension of this early work showed that the Fluorescein dyes, particularly Eosin, can oxidize many aromatic compounds via this mechanism. In addition, it was found that the ultraviolet flash photolysis of many aromatics leads to the formation of the hydrated electron. These aspects were extended after 1962 with particular emphasis on their significance in photobiology.

B. Low-Temperature Photoequilibria Between F and F' Centers

The object of this research was to investigate the fast processes involved in the optical bleaching of F centers in KCl and the formation of F' centers. The measurements were done at low temperatures where steady illumination does not induce any significant optical bleaching of the F center. However, it was found that a substantial decrease in the F band takes place when the colored crystal is irradiated with a green light flash, accompanied by the formation of additional absorption in the red F' region. Conversely, the irradiation with a red light flash causes a fast growth of the F band followed by a return to the initial condition. It was found that the extent of these changes depends on the spectrum and intensity of the monitoring steady illumination required for the measurement of the absorption spectra. This was the first indication that the detection system itself is involved in the observed color center transformations. The detailed analysis shows that the monitoring beam establishes an equilibrium between F centers and F' centers, determined by the photoionization efficiency of each center and the overlap of their absorption bands. The application of the light flash disturbs the equilibrium towards either direction, followed by a return to steady state induced by the monitoring light plus thermal processes. The detailed analysis (III A - 7,8) led to the determination of the photoionization efficiency of the F center and the relative electron capture cross sections of the F center and the negative ion vacancy in KCl. The results are in reasonable agreement with the values determined by photoconductivity measurements.

C. Optical Formation of F-aggregate Centers and Their Spin-Metastable States

Considerable emphasis in this program was given to the optical conversion of F centers to intermediates and higher aggregates. In an early study, the kinetics of F center growth caused by irradiation after optical bleaching was investigated (Table III A -5). It was found that the energy required to restore optically bleached F centers is close to the energy required for the initial coloration of fresh KCl. This result shows that initial coloration utilizes vacancies already in the crystal. The kinetics of recovery are second order in the number of unrecovered F centers so that the electrons utilized in recovery are not generated directly in the bulk lattice. The recovery process led to the complete destruction of the M and R centers produced by optical bleaching. It was proposed that recovery by irradiation involves the destruction of the aggregate centers and the formation of F centers in an essentially reversible process.

In the course of the photoequilibrium studies (Paragraph B) it was noted that the transition rates between F centers and F' centers are modified when M centers or higher aggregates are also present in the KCl crystal. A more detailed investigation showed that illumination of KCl with F light at low temperature leads to the formation of new temporary absorptions under such conditions. The latter correspond to spectral changes associated with the spin-metastable M center and R center as studied by ENDOR measurements. The investigation of the M center triplet state (III A 19) showed that it is formed by energy transfer from the excited state of the F center and that it decays with a temperature-dependent lifetime in the dark corresponding to a thermal activation energy of 0.064 ev in competition with

a 45 second half-time transition. The dark half-time of the R center quartet state was found to be 14 sec and independent of temperature.

In a recent extension of this work (Progress Report No.10, February 1968) the metastable centers in NaCl were investigated using the method of temporary dichroism. This method led to an energy diagram for the R center quartet state that is qualitatively similar to the case of KCl as determined by spectral splitting under uniaxial stress. Additional work with KI and consideration of results obtained elsewhere led to Mollwo-Ivey plots of the M center triplet state and R center quartet state in various alkali halide crystals. In the course of these investigations it was desired to study the influence of temperature on the optical conversion of F centers to higher aggregates in KCl. This work led to the observation of new absorption bands, stable at room temperature, designated as T bands (III A-13). An effort was made to identify the three T bands in KCl with specific structures by studying their low temperature interconversions (III A-16). It was found that the absorptions at 894 nm (T_2) and 992 nm (T_3) can be converted into one another by optical transitions while the band at 839 nm (T_1) is distinct. It was concluded that the three T bands in KCl are due to F aggregates higher than F_3 and that T_2 and T_3 are probably isomers of F_4 .

Another investigation was directed towards clarifying the mechanism of the optical conversion of F centers to M centers in KCl near room temperature, which involves a combination of electronic and ionic motions. A new technique was employed in which the bleaching is effected with repetitive light pulses of variable frequency. The dependence of the quantum yield on repetition rate gives information about the dark processes that cannot be

obtained by constant irradiation methods. It was found that the initial rate of M center formation increases with the time between light pulses, while the maximum yield of M centers behaves in the opposite way. The detailed investigation based on the dependence of the conversion quantum efficiency on temperature, flash intensity, repetition rate, and initial F center density led to a new model for the formation of M centers (III A-23). It is proposed that light absorption by the F center induces tunneling of an electron from the F center to a nearby F center. The resulting entity is referred to as F'_α . The F'_α complex can form an M center by diffusion of the vacancy to the F' moiety, in competition with optical and thermal ionization leading to isolated F' and α centers, or the reverse tunneling step. The initial rate of M center formation increases with decreasing pulse repetition rate because more time is available for the dark diffusional process. On the other hand, the higher maximum M center yield with increasing repetition rate results from bimolecular reactions between separated F' and α centers because of higher time-average concentrations. This model explains the concentration quenching of F center fluorescence in the early stages of bleaching prior to aggregation because the tunneling of an electron from the excited F center to a nearby F center followed by the reverse tunneling step competes with radiative decay of the excited F center.

D. Effects of Radiation on Surface Properties of Alkali Halide Crystals

The basic objective of these studies was to investigate radiation damage in alkali halide crystals with emphasis on the interaction of point defects such as color centers with dislocations. The earlier work was done in connection with sliding friction of single crystals as determined under carefully controlled conditions. It was found that the static friction of

KCl has contributions from adhesive energy and plastic flow, which depend differently on the normal load, while the corresponding frictional coefficients vary with the square root of the F center density. In the case of sliding friction the contributions from plastic flow and plowing depend linearly on the normal load, and again the coefficients vary with the square root of the F center density. The comparison to frictional theory shows that the results agree best with the plastic-shear theory as opposed to the elastic-shear theory. The surface friction of mechanically polished KCl is best described by plastic deformation of contacting asperities with appropriate load dependence terms for the static and low-speed sliding cases. This work showed that fundamental information about the frictional process can be deduced by studying irradiation effects on a particular slide, in contrast to the usual procedure of comparing results obtained with related but different materials (III A-11,18).

A second aspect of this work involved measuring the surface energy of KCl, a subject which has received considerable theoretical and experimental interest. Again, irradiation provides a convenient method for introducing point defects (color centers and hardening centers) which interact in turn with dislocations. The Gilman-Obreimov method was employed in which the critical energy required to reinitiate a crack is related to the surface energy. The earlier work (III A 12,15) showed that there are two contributions to the surface energy induced by irradiation. One contribution depends on the square root of the F center density and is attributed to the energy dissipated in plastic flow. The other term depends on the two-thirds power of the F center density and is identified with the effect of point defects on the strength of the crystalline bonds at the crack tip. The changes in these parameters, induced by optical bleaching of the F centers

and the comparison with additively-colored KCl, show that the predominant effect is due to a colorless hardening center formed with the F centers. The hardening centers are believed to be interstitial defects which cause assymmetric lattice strain. Information about the hardening centers have been obtained by pulse annealing experiments which lead to a thermal activation energy of 0.52 ev. The recent work (III B-32) shows that the apparent surface energy determined by the slow cleavage method depends on the loading speed, which can be explained by the contribution of plastic deformation at the crack tip to fracture energy. The best value of the KCl surface energy from this work of 131 ± 26 is in good agreement with recent theoretical calculations.

E. Mechanism of Spectral Sensitization of Zinc Oxide Photoconductivity

The spectral sensitization of electronic processes in solids is a well known phenomenon which includes such diverse applications as silver halide photography and photosynthesis in green plants. The sensitization of photoconductivity in organic and inorganic photoconductors has become important recently in connection with electrophotographic processes. However, the basic mechanism by which light absorbed in the dye leads to additional conduction electrons in the substrate is not known. The object of the work in this laboratory was to explore the fundamental mechanism of spectral sensitization using a reproducible system amenable to theoretical analysis. Most of the work has been done with evaporated zinc oxide films on a flat glass substrate in surface contact with adsorbed eosin or another sensitizing dye. The earlier work involved measuring the resistance changes in the dark when the dye layer is formed and the dependence of the sensitized photoeffect on pertinent variables including light intensity, spectrum,

zinc oxide dark current, and temperature (III A-14,20). It was found that the addition of the dye film leads to an increase of the zinc oxide resistivity for both n-type and p-type photoconducting dyes. The increase in conductivity caused by illumination of the dye-ZnO surface cell with visible light never exceeds the decrease upon dyeing. This observation led to a general model in which the dye abstracts conduction electrons in the dark, which are returned when the dye is excited with visible light. The detailed Schottky barrier model predicts a dependence of the fractional dark transfer of conduction electrons on dye molecule energy levels in good agreement with the measurements. In addition, this theory explains the observed linear dependence of the sensitized photoeffect on ZnO dark current, the approximate square root dependence on light intensity, and the buildup and decay kinetics measured with steady and pulse light sources.

The more recent work (III A-22) has been done with an apparatus in which a dye film from sub-monolayer to many layers can be formed on the ZnO surface in a vacuum system. The photoconductivity and pulsed field effect can be measured in situ without disturbing the system. The results show that two regimes of sensitization are involved. The dark transfer of electrons from the ZnO substrate to the dye molecules requires only monolayer coverage. The traps are postulated to be ZnO surface states at a particular energy level whose cross section is enhanced by the adsorbed dye molecule. The return of these trapped electrons by optical excitation of the dye molecules explains sensitization by singly-adsorbed dye molecules or fractional monolayers. A distinct thick dye film effect has been identified in which the dye molecules distant from the interface are excited. A comparison of the field effect kinetics to those of the undyed ZnO film indicates that

the enhanced conductivity results from changes in the ZnO depletion layer. According to this model, thick film sensitization, which can be manifest as photoconductivity or a photovoltaic effect, can be described in terms of a capacitor formed by the ZnO and dye layers. This type of investigation makes it possible to describe the ability of a particular dye to sensitize a good substrate in terms of well-defined energy parameters of the individual components.

In connection with this phase of the project the 1st International Conference on Photosensitization in Solids was organized by the Principal Investigator and was held at IIT in June 1964. The 2nd International Conference was held at the University of Arizona (Tucson) under the direction of G. Tollin in January 1968, and the 3rd International Conference is being planned for Sarlat, France for September 1971 under the direction of J. Bourdon. The invited papers of the 1st Conference were published in the Journal of Physical Chemistry, Vol. 69, March 1965, and the papers of the 2nd Conference were published in Photochemistry and Photobiology, Vol. 8, November 1968.

TABLE I. RESEARCH PROJECTS

TABLE II. SCIENTIFIC PERSONNEL

TABLE III. REPORTING OF RESEARCH

A. Journal Articles

B. Meeting Papers

C. Theses

RESEARCH PROJECTS

- 1) Mechanism of the optical F-to-F' interconversions in KCl
1958 - 1965
- 2) Flash photolysis studies of dye sensitized photochemical reactions
1958 - 1962
- 3) Optical bleaching and irradiation recovery of F centers in KCl
1959 - 1961
- 4) Dye-sensitized photoconductivity of zinc oxide thin films
1961 - 1970
- 5) Effect of radiation on sliding friction in alkali halide crystals
1962 - 1965
- 6) Effect of radiation on surface energy of alkali halide crystals
1962 - 1970
- 7) Production of new F-aggregate color centers in KCl
1963 - 1966
- 8) Optical conversion of F centers to M centers in KCl induced by
repetitive pulse illumination
1966 - 1970
- 9) Properties of the spin-metastable color centers
1966 - 1970

SCIENTIFIC PERSONNEL

Dr. L. I. Grossweiner (Principal Investigator)	1958-1970
Dr. E. F. Zwicker (Research Associate)	1958-1968
L. E. Silverman (Research Assistant)	1959-1960
Dr. A. R. Reinberg (Research Assistant)	1958-1961
Dr. A. Costikas (Research Assistant)	1960-1962
Dr. S. J. Dudkowski (Research Assistant)	1961-1967
Dr. J. G. Ring (Research Assistant)	1962-1965
R. T. McCall (Research Assistant)	1963-1970
Dr. T. K. Bhattacharya (Research Assistant)	1963-1965
Dr. G. Jirgal (Research Assistant)	1963-1964
F. J. Dudek (Research Assistant)	1963-1968
A. Kepka (Research Assistant)	1965-1967
S. Chung (Research Assistant)	1966-1967
D. Leong (Research Assistant)	1966-1970
K. Wier (Research Assistant)	1966-1967
Dr. W. D. Brennan (Research Assistant)	1967-1970

REPORTING OF RESEARCH

A. Journal Articles

- 1) Transient Processes in the Optical Bleaching of F and F' Centers in Potassium Chloride.
A.R.Reinberg and L.I.Grossweiner
J. Chem. Phys. 30 1616-1617 (1959)
- 2) Primary Processes in the Photochemistry of Eosin
L.I.Grossweiner and E.F.Zwicker
J. Chem. Phys. 31 1141-1142 (1959)
- 3) Free Radicals from the Flash Photolysis of Phenol
L.I.Grossweiner and E.F.Zwicker
J. Chem. Phys. 32, 305-306 (1960)
- 4) Flash Photolysis
L.I.Grossweiner
Scientific American 202, 134-145 (1960)
- 5) Bleaching and Recovery of F Centers in KCl.
L.I.Silverman and L.I.Grossweiner
Phys.Rev. 121, 1072-75 (1961)
- 6) Transient Measurements of Photochemical Processes in Dyes:
I. The Photosensitized Oxidation of Phenol by Eosin and Related Dyes.
L.I.Grossweiner and E.F.Zwicker
J. Chem. Phys. 34, 1411-1417 (1961)
- 7) Low-Temperature Optical Bleaching of F Centers in KCl.
A.R.Reinberg and L.I.Grossweiner
Phys. Rev. 122, 1734-41 (1961)
- 8) The Photoequilibrium between KCl F and F' Centers at 80°K
A. Costikas and L.I.Grossweiner
Phys. Rev. 126, 1410-20 (1962)
- 9) Transient Measurements of Photochemical Processes in Dyes. II.
The Mechanism of the Photosensitized Oxidation of Aqueous Phenol by Eosin
E.F.Zwicker and L.I.Grossweiner
J. Phys. Chem. 67, 549-555 (1963)
- 10) Sensitization of Chemical and Photoconductive Processes by the Fluorescein Dye Triplet States.
L.I.Grossweiner
PHYSICAL PROCESSES IN RADIATION BIOLOGY (Ed. Augenstein, Mason, and Rosenberg; Academic Press, New York, 1964) pp. 287-303

III, contd.

- 11) The Effects of X-Ray Irradiation on the Self-Friction of Potassium Chloride.
E.J.Zwicker and G.H.Jirgal, Jr.
Wear, 7, 39-47 (1964)
- 12) Effect of Co-60 Gamma Irradiation on Surface Energy of KCl
T.K.Bhattacharya, H.Nonnenmacher, and L.I.Grossweiner
J. Appl. Phys. 35, 1352-53 (1964)
- 13) Occurrence of New Color Center Absorptions in KCl
J.G.Ring and L.I.Grossweiner
J. Appl. Phys. 35, 2257-58 (1964)
- 14) Sensitization of Photoconduction in a Zinc Oxide Film by Eosin
S.J.Dudkowski and L.I.Grossweiner
J. Opt. Soc. Am., 54, 586-591 (1964)
- 15) Ionizing Irradiation Effects on the Fracture Surface Energy of KCl
T.K.Bhattacharya and E.F.Zwicker
J. Appl. Phys. 37, 771-777 (1966)
- 16) The Formation and Bleaching Properties of the T Bands in KCl
J.G.Ring and L.I.Grossweiner
J. Appl. Phys. 37, 1852-1857 (1966)
- 17) The Study of Labile States of Biological Molecules with Flash Photolysis.
L.I.Grossweiner
Advances in Radiation Biology, Vol.2, pp. 83-133 (1966) Academic Press, New York.
- 18) Effects of X-Ray Irradiation on the Self-Friction of Potassium Chloride.
G.H.Jirgal, Jr. and E.F.Zwicker
J. Appl. Phys., 37, 4358-4363 (1966) (COO-1052-1)
- 19) Metastable F Aggregate Color Centers in Irradiated KCl
R.T.McCall and L.I.Grossweiner
J. Appl. Phys. 38, 284-288 (1967) (COO-1052-2)
- 20) Spectral Sensitization of ZnO Thin Films with Organic Dyes.
S.J.Dudkowski, A.G.Kepka, and L.I.Grossweiner
J. Phys. Chem. Solids 28, 485-493 (1967). (COO-1052-3)
- 21) A Chemical Polishing Technique for KCl.
D.Chesters and E.F.Zwicker
J.Appl.Phys., 38, 1983-84 (1967) (COO-1052-4)
- 22) Photo-Induced Surface Charge Density Effects in Dye-Sensitized Zinc Oxide.
L.I.Grossweiner and W.D.Brennan
J. Phot. Sci. (in press) (1970) (COO-1052-11)
- 23) The Optical Conversion of F Centers to M Centers in KCl with Repetitive Light Pulses.
F.J.Dudek and L.I.Grossweiner
J.Phys.Chem.Solids, 30, 2023-2035 (1969) (COO-1052-10)

III, contd.

B. Meeting Papers

- 1) Transient Processes in the Optical Bleaching of Color Centers in Potassium Chloride.
L.I.Grossweiner and A.R.Reinberg
American Physical Society, Washington, D. C., April 30, 1959.
- 2) The Investigation of the Chemical Reactivity of Excited Molecular States of Dyes with Flash Photolysis Methods.
L.I.Grossweiner and E.F.Zwicker
Symposium on Molecular Fluorescence, Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, March 29, 1960.
- 3) Optical Bleaching and Recovery of F Centers.
L.I.Grossweiner and Loretta E. Silverman
American Physical Society, Washington, D. C., April 25, 1960
- 4) The Low-Temperature Optical Bleaching of F Centers in Potassium Chloride.
L.I.Grossweiner and A.R.Reinberg
Midwest Solid State Conference, University of Nebraska, Lincoln, Nebraska, October 22, 1960.
- 5) Low-Temperature Bleaching of F Centers in KCl.
A.R.Reinberg and L.I.Grossweiner
American Physical Society, Chicago, Illinois, November 26, 1960.
- 6) The Photoequilibrium Between F and F' Centers in KCl at 80°K.
A.Costikas and L.I.Grossweiner
Midwest Solid State Conference, Argonne National Laboratory, Argonne, Illinois; October 21, 1961.
- 7) The Photoequilibrium Between F and F' Centers in KCl at 80°K.
A. Costikas and L.I.Grossweiner
American Physical Society, Chicago, Illinois; November 24, 1961
- 8) The Application of Flash Photolysis to an Investigation of the Oxidation of Aqueous Phenol as Photosensitized by Eosin.
L.I.Grossweiner and E.F.Zwicker
Mid-America Spectroscopy Symposium
Chicago, Illinois, April 30-May 3 (1962) (Invited)
- 9) Dye-Sensitized Photoconductivity of Zinc Oxide Films.
L.I.Grossweiner and S.J.Dudkowski
American Physical Society, Northwestern University, June 19-21 (1962)
- 10) Dye-Sensitized Photoconductivity of Zinc Oxide Films.
L.I.Grossweiner and S.J.Dudkowski
Black Hills Summer Conference on Transport Phenomena
Rapid City, South Dakota, August 21-23 (1962)

III, contd.

- 11) Flash Bleaching of M Centers in KCl at Room Temperature.
James G. Ring and L.I.Grossweiner
Midwest Solid State Conference,
Kansas City, Missouri, October 19-20 (1962)
- 12) Sensitization of Chemical and Photoconductive Processes by Fluorescein
Dye Triplet States.
L.I.Grossweiner
Symposium on Physical Mechanisms in Radiation Biology
Michigan State University, May 5-8 (1963) (Invited)
- 13) The Effects of X-Ray Irradiation on the Self-Friction of Potassium
Chloride.
E.F.Zwicker and G.H.Jirgal, Jr.
Solid State Friction Conference, Midwest Research Institute,
Kansas City, Sept. 16-18, 1963.
- 14) Sensitized Photoconduction in Eosin-Zinc Oxide Double Layers.
L.I.Grossweiner and S.J.Dudkowski
American Physical Society, Chicago, Illinois, October 18-19, 1963.
- 15) Effect of Co-60 Gamma Irradiation on Surface Energy of KCl.
T.K.Bhattacharya and L.I.Grossweiner
American Physical Society, New York, January 22-25, 1964
- 16) Occurrence of a New Aggregate Color Center Band in KCl.
L.I.Grossweiner and J.G.Ring
American Physical Society, New York, January 22-25, 1964.
- 17) The Occurrence and Photobleaching Properties of the T bands.
J.G.Ring and L.I.Grossweiner
Midwest Solid State Conference, Kansas State University,
Manhattan, Kansas, October 16-17, 1964.
- 18) Low Temperature Optical Bleaching of the T Centers in KCl.
J.G.Ring and L.I.Grossweiner
American Physical Society, Chicago, Illinois, October 23-24, 1964.
- 19) Dependence of the Friction of KCl upon F-Center Concentration.
G.H.Jirgal and E.F.Zwicker
American Physical Society, Chicago, Illinois, October 23-24, 1964.
- 20) Investigation of Color Center Transformations with Pulse Bleaching Methods.
L.I.Grossweiner, R.T.McCall, and J.G.Ring
International Symposium on Color Centers in Alkali Halides,
University of Illinois, Urbana, Illinois, October 11-13, 1965.
- 21) Changes in Fracture Surface Energy of KCl produced by Ionizing Irradiation.
T.K.Bhattacharya and E.F.Zwicker
American Physical Society, Chicago, Illinois, October 28-30, 1965.

III, contd.

- 22) Transient M Center Triplet Absorptions in KCl.
R.T.McCall and L.I.Grossweiner
Midwest Solid State Conference,
Illinois Institute of Technology, Chicago, Illinois, October 27-28, 1965.
- 23) Low-Temperature Photoequilibria in X-Rayed KCl.
L.I.Grossweiner and R.T.McCall
American Physical Society, Durham, N.C., March 28-31, 1966.
- 24) Spectral Sensitization of ZnO Thin Films.
A.G.Kepka, S.J.Dudkowski, and L.I.Grossweiner
14'th Midwest Solid State Conference, Ames, Iowa, October 1, 1966.
- 25) Metastable F-Aggregate Centers in Irradiated KCl.
L.I.Grossweiner and R.T.McCall
14'th Midwest Solid State Conference, Ames, Iowa, October 1, 1966.
- 26) Spectral Sensitization of ZnO Conductivity by Organic Dyes.
L.I.Grossweiner, A.G.Kepka, and S.J.Dudkowski
American Physical Society, New York, January 30-February 2, 1967 (COO-1052-5)
- 27) Optical Conversion of F Centers to M Centers in KCl Induced by
Intermittent Light.
F.Dudek, K.Weir, and L.I.Grossweiner
American Physical Society, Chicago, Ill., March 27-30, 1967. (COO-1052-6)
- 28) Spectral Sensitization of Zinc Oxide Thin Films. (invited paper)
L.I.Grossweiner
SPSE Symposium on Unconventional Photographic Processes (Invited)
Washington, D.C., October 26-27, 1967
- 29) Sensitization of Photoconductive Effects in Zinc Oxide - A Review.
L.I.Grossweiner
Second International Conference on Photosensitization in Solids
Tucson, Arizona, January 29-31, 1968. (invited paper) (COO-1052-8)
- 30) Fracture Surface Energy of KCl.
D.Leong and E.F.Zwicker
Midwest Solid State Conference, Lawrence, Kansas, October 26, 1968.
- 31) The Surface Energy of Solids.
E.F.Zwicker
AAPT, Chicago Section Meeting, Evanston, Ill., November 9, 1968.
- 32) Effect of Hardening on the Fracture Energy of KCl.
D.Leong and E.F.Zwicker
Midwest Solid State Conference, Iowa City, Iowa, October 18, 1969.
- 33) Dye-Sensitized Surface Photoeffect in ZnO Thin Films.
W.D.Brennan and L.I.Grossweiner
Midwest Solid State Conference, Iowa City, Iowa, October 18, 1969.

III, contd.

- 34) Photo-Induced Surface Charge Density Effects in Dye-Sensitized Zinc Oxide.
L.I.Grossweiner and W.D.Brennan
The Royal Photographic Society of Great Britain,
Oxford, England, September 30-October 3, 1969. (Invited)

C. Theses

- 1) Transient Bleaching of Color Centers in KCl.
Alan R. Reinberg
M.S. Thesis, Illinois Institute of Technology, June 1959
- 2) Bleaching and Recovery of Color Centers in Potassium Chloride.
Loretta E. Silverman
M.S. Thesis, Illinois Institute of Technology, June 1960
- 3) Transient Bleaching of F-Centers in Potassium Chloride.
Alan R. Reinberg
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- 4) The Photoequilibrium between F and F' Centers in Potassium Chloride.
Athanssios Costikas
Ph.D. Thesis, Illinois Institute of Technology, June 1962
- 5) The Effects of X-Irradiation Upon Friction of Potassium Chloride.
George H. Jirgal, Jr.
M.S. Thesis, Illinois Institute of Technology, June 1963
- 6) Effect of Co-60 Gamma-Irradiation on Surface Energy of KCl.
Tapan Kumar Bhattacharya
M.S. Thesis, Illinois Institute of Technology, January 1964
- 7) The Effects of X-Ray Irradiation on Self-Friction in KCl.
George H. Jirgal, Jr.
Ph.D. Thesis, Illinois Institute of Technology, January 1965
- 8) Ionizing Irradiation Effects on the Fracture Surface Energy of Potassium Chloride.
Tapan Kumar Bhattacharya
Ph.D. Thesis, Illinois Institute of Technology, January 1966.
- 9) The Formation and Bleaching Properties of the T Bands in KCl.
J. G. Ring
Ph.D. Thesis, January 1966, Illinois Institute of Technology.
- 10) Optical Growth of the M Band in Additively Colored KCl Using Pulsed Bleaching Light.
Keith E. Wier
M.S. Thesis, June 1967, Illinois Institute of Technology

III, contd.

- 11) The Spectral Sensitization of Zinc Oxide by Organic Dyes.
Alan George Kepka
M.S. Thesis, January 1968, Illinois Institute of Technology
- 12) The Thermal and Optical Properties of the T Bands.
Shuh-Yun Chung
M.S. Thesis, June 1968, Illinois Institute of Technology
- 13) A New Spectral Sensitization Mechanism in Zinc Oxide Thin Films.
Stanley Joseph Dudkowski
Ph.D. Thesis, June 1968, Illinois Institute of Technology

D. Reports

Progress Report No. 1	January 1959	4 pp	
Progress Report No. 2	February 1960	10 pp	
Progress Report No. 3	February 1961	17 pp	
Progress Report No. 4	February 1962	18 pp	
Progress Report No. 5	February 1963	22 pp	
Progress Report No. 6	February 1964	25 pp	
Progress Report No. 7	February 1965	26 pp	
Progress Report No. 8	February 1966	20 pp	
Progress Report No. 9	February 1967	21 pp	COO-1052-7
Progress Report No.10	February 1968	17 pp	COO-1052-9
Final Report	January 1970	22 pp	COO-1052-12