

Polymers for High Technology

Electronics and Photonics



ACS SYMPOSIUM SERIES **346**

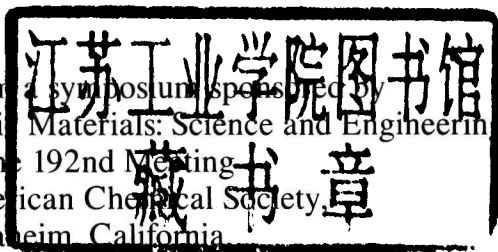
Polymers for High Technology

Electronics and Photonics

Murrae J. Bowden, EDITOR
Bell Communications Research

S. Richard Turner, EDITOR
Eastman Kodak Company

Developed from a symposium sponsored by
the Division of Polymer Materials: Science and Engineering
at the 192nd Meeting
of the American Chemical Society
Anaheim, California
September 7-12, 1986



American Chemical Society, Washington, DC 1987



Library of Congress Cataloging-in-Publication Data

Polymers for high technology.

(ACS symposium series, ISSN 0097-6156; 346)

Includes bibliographies and indexes.

1. Polymers and polymerization—Congresses.
2. Photoresists—Congresses. 3. Microlithography—
Materials—Congresses. 4. Microelectronics—
Materials—Congresses.

I. Bowden, Murrae J., 1943–. II. Turner,
S. Richard, 1942–. III. American Chemical Society.
Division of Polymeric Materials: Science and
Engineering. IV. American Chemical Society. Meeting
(192nd: 1986: Anaheim, Calif.) V. Series.

TK7871.15.P6P627 1987 668.9 87-14573

ISBN 0-8412-1406-9

Copyright © 1987

American Chemical Society

All Rights Reserved. The appearance of the code at the bottom of the first page of each chapter in this volume indicates the copyright owner's consent that reprographic copies of the chapter may be made for personal or internal use or for the personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay the stated per copy fee through the Copyright Clearance Center, Inc., 27 Congress Street, Salem, MA 01970, for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to copying or transmission by any means—graphic or electronic—for any other purpose, such as for general distribution, for advertising or promotional purposes, for creating a new collective work, for resale, or for information storage and retrieval systems. The copying fee for each chapter is indicated in the code at the bottom of the first page of the chapter.

The citation of trade names and/or names of manufacturers in this publication is not to be construed as an endorsement or as approval by ACS of the commercial products or services referenced herein; nor should the mere reference herein to any drawing, specification, chemical process, or other data be regarded as a license or as a conveyance of any right or permission, to the holder, reader, or any other person or corporation, to manufacture, reproduce, use, or sell any patented invention or copyrighted work that may in any way be related thereto. Registered names, trademarks, etc., used in this publication, even without specific indication thereof, are not to be considered unprotected by law.

PRINTED IN THE UNITED STATES OF AMERICA

ACS Symposium Series

M. Joan Comstock, *Series Editor*

1987 Advisory Board

Harvey W. Blanch
University of California—Berkeley

Alan Elzerman
Clemson University

John W. Finley
Nabisco Brands, Inc.

Marye Anne Fox
The University of Texas—Austin

Martin L. Gorbaty
Exxon Research and Engineering Co.

Roland F. Hirsch
U.S. Department of Energy

G. Wayne Ivie
USDA, Agricultural Research Service

Rudolph J. Marcus
Consultant, Computers &
Chemistry Research

Vincent D. McGinniss
Battelle Columbus Laboratories

W. H. Norton
J. T. Baker Chemical Company

James C. Randall
Exxon Chemical Company

E. Reichmanis
AT&T Bell Laboratories

C. M. Roland
U.S. Naval Research Laboratory

W. D. Shults
Oak Ridge National Laboratory

Geoffrey K. Smith
Rohm & Haas Co.

Douglas B. Walters
National Institute of
Environmental Health

Foreword

The ACS SYMPOSIUM SERIES was founded in 1974 to provide a medium for publishing symposia quickly in book form. The format of the Series parallels that of the continuing ADVANCES IN CHEMISTRY SERIES except that, in order to save time, the papers are not typeset but are reproduced as they are submitted by the authors in camera-ready form. Papers are reviewed under the supervision of the Editors with the assistance of the Series Advisory Board and are selected to maintain the integrity of the symposia; however, verbatim reproductions of previously published papers are not accepted. Both reviews and reports of research are acceptable, because symposia may embrace both types of presentation.

Preface

THE ELECTRONICS REVOLUTION, WHICH BEGAN with the invention of the transistor at Bell Telephone Laboratories in 1948, has continued at a frenetic pace and shows no sign of abating. Polymers have played and continue to play an integral part in this revolution in a wide variety of applications. For example, the increasing complexity of microelectronic circuits has been due in no small measure to improvements in the lithographic art. Advances in the design and development of polymeric resists have been pivotal to lithography. Polymers play an enormously important role in the packaging and interconnection of electronic components and find wide use in other applications such as dielectrics. Optical technology, with its tremendous potential for applications in communications, memory, and information retrieval, has given impetus to research on such topics as organic materials (including polymers) for nonlinear optics and optical fiber coatings.

Definitive advances in polymeric materials pertaining to these many technological thrusts continue to be made, even in technologies we might consider to be relatively “mature”, for example, resist materials for microlithography. Here, new materials and processes will be required in the not-too-distant future to meet the demands of new and evolving lithographic processes. In some of the relatively recent areas of research, such as polymers for nonlinear optics, molecular electronics, and conducting polymers, many fundamental scientific principles are still not fully understood. Real breakthroughs will be needed to convince skeptics in the solid-state community of the potential advantages offered by organic materials in applications currently limited by the properties of conventional semiconductor materials.

These two powerful forces—the ongoing electronic and photonic revolution, and the significant potential of polymers to contribute to the materials needs of that revolution—continue to stimulate chemists to explore the fundamental, chemically related principles underlying these technologies. Heightened awareness of research opportunities in these areas can in turn lead to further advances.

This book has been organized into eight sections, each representing a specific field. Each section contains an introduction written by the respective session chairperson of the symposium from which this book was developed. All session chairs are recognized experts in their fields. We are indebted to many people and organizations for making the symposium

possible, especially the session chairs who assembled the technical presentations and served as coordinators of the reviewing process. We are particularly grateful to the Petroleum Research Foundation for providing a substantial grant that allowed several overseas speakers to attend the symposium. We also acknowledge the generous financial support of the IBM Corporation, Eastman Kodak Company, AZ Photoproducts Division of American Hoechst Corporation, Dynachem Division of Morton Thiokol Corporation, and the Division of Polymeric Materials: Science and Engineering. We are especially indebted to Lois Damick of Bell Communications Research who handled most of the administrative aspects in preparing this volume. Finally, we thank Robin Giroux and the production staff of the ACS Books Department for their efforts in getting this book published successfully.

MURRAE J. BOWDEN
Navesink Research and Engineering Center
Bell Communications Research
Red Bank, NJ 07701-7020

S. RICHARD TURNER
Corporate Research Laboratories
Eastman Kodak Company
Rochester, NY 14650

March 26, 1987

Recent ACS Books

Personal Computers for Scientists: A Byte at a Time

By Glenn I. Ouchi

288 pp; clothbound; ISBN 0-8412-1001-2

The ACS Style Guide: A Manual for Authors and Editors

Edited by Janet S. Dodd

264 pp; clothbound; ISBN 0-8412-0917-0

Silent Spring Revisited

Edited by Gino J. Marco, Robert M. Hollingworth, and William Durham

214 pp; clothbound; ISBN 0-8412-0980-4

Chemical Demonstrations: A Sourcebook for Teachers

By Lee R. Summerlin and James L. Ealy, Jr.

192 pp; spiral bound; ISBN 0-8412-0923-5

Phosphorus Chemistry in Everyday Living, Second Edition

By Arthur D. F. Toy and Edward N. Walsh

342 pp; clothbound; ISBN 0-8412-1002-0

Pharmacokinetics: Processes and Mathematics

By Peter G. Welling

ACS Monograph 185; 290 pp; ISBN 0-8412-0967-7

*Metal Complexes in Fossil Fuels: Geochemistry,
Characterization, and Processing*

Edited by Royston H. Filby and Jan F. Branthaver

ACS Symposium Series 344; 436 pp; ISBN 0-8412-1404-2

*Proteins at Interfaces: Physicochemical
and Biochemical Studies*

Edited by John L. Brash and Thomas A. Horbett

ACS Symposium Series 343; 706 pp; ISBN 0-8412-1403-4

Ordered Media in Chemical Separations

Edited by Willie L. Hinze and Daniel W. Armstrong

ACS Symposium Series 342; 293 pp; ISBN 0-8412-1402-6

Sources and Fates of Aquatic Pollutants

Edited by Ronald A. Hites and S. J. Eisenreich

Advances in Chemistry Series 216; 558 pp; ISBN 0-8412-0983-9

Nucleophilicity

Edited by J. Milton Harris and Samuel P. McManus

Advances in Chemistry Series 215; 494 pp; ISBN 0-8412-0952-9

For further information and a free catalog of ACS books, contact:

American Chemical Society

Distribution Office, Department 225

1155 16th Street, NW, Washington, DC 20036

Telephone 800-227-5558

Contents

| | |
|----------------------|-----------|
| Preface | ix |
|----------------------|-----------|

FUNDAMENTALS IN RADIATION CHEMISTRY OF POLYMERS

| | |
|--|-----------|
| 1. Development of Radiation Chemistry | 5 |
| G. Arthur Salmon | |
| 2. Primary Action of Ionizing Radiation on Condensed Systems | 16 |
| J. K. Thomas and G. Beck | |
| 3. Historical Outline of Radiation Effects in Polymers | 31 |
| Adolphe Chapiro | |
| 4. Main Reactions of Chlorine- and Silicon-Containing Electron and Deep-UV (Excimer Laser) Negative Resists | 37 |
| Seiichi Tagawa | |
| 5. Relations Between Photochemistry and Radiation Chemistry of Polymers | 46 |
| J. E. Guillet | |

RESIST MATERIALS FOR ELECTRON AND X-RAY LITHOGRAPHY

| | |
|---|------------|
| 6. Characteristics of a Two-Layer Resist System Using Silicone-Based Negative Resist for Electron-Beam Lithography | 67 |
| Toshiaki Tamamura and Akinobu Tanaka | |
| 7. Phenolic Resin-Based Negative Electron-Beam Resists | 77 |
| H. Shiraishi, N. Hayashi, T. Ueno, O. Suga, F. Murai, and S. Nonogaki | |
| 8. Electron-Beam Sensitivity of Cross-Linked Acrylate Resists | 86 |
| Nigel R. Farrar and Geraint Owen | |
| 9. A "One-Layer" Multilayer Resist | 101 |
| R. D. Allen, S. A. MacDonald, and C. G. Willson | |
| 10. New Silicon-Containing Electron-Beam Resist Systems | 110 |
| E. Reichmanis, A. E. Novembre, R. G. Tarascon, and A. Shugard | |
| 11. Lithographic Evaluation of Poly(methyl methacrylate)-graft-poly(dimethylsiloxane) Copolymers | 122 |
| Murrae J. Bowden, A. S. Gozdz, C. Klausner, J. E. McGrath, and S. Smith | |
| 12. Acid-Catalyzed Thermolytic Depolymerization of Polycarbonates: A New Approach to Dry-Developing Resist Materials | 138 |
| J. M. J. Fréchet, E. Eichler, M. Stanculescu, T. Iizawa, F. Bouchard, F. M. Houlihan, and C. G. Willson | |
| 13. Sensitivity of Polymer Blends to Synchrotron Radiation | 149 |
| J. A. Jubinsky, R. J. Groele, F. Rodriguez, Y. M. N. Namasté, and S. K. Obendorf | |

RESIST MATERIALS AND PROCESSING
FOR OPTICAL LITHOGRAPHY

| | |
|---|------------|
| 14. A New High-Sensitivity, Water-Developable Negative Photoresist | 162 |
| Anders Hult, Otto Skolling, Sven Göthe, and Ulla Mellström | |
| 15. Soluble Polysilanes in Photolithography | 170 |
| R. D. Miller, D. Hofer, J. Rabolt, R. Sooriyakumaran, C. G. Willson, G. N. Fickes, J. E. Guillet, and J. Moore | |
| 16. Evaluation of Water-Soluble Diazonium Salts as Contrast-Enhancement Materials Using a g-Line Stepper | 188 |
| S.-I. Uchino, T. Ueno, T. Iwayanagi, H. Morishita, S. Nonogaki, S.-I. Shirai, and N. Moriuchi | |
| 17. Thermally Stable, Deep-UV Resist Materials | 200 |
| S. Richard Turner, K. D. Ahn, and C. G. Willson | |
| 18. A Silicon-Containing Positive Photoresist Developable with Aqueous Alkaline Solution | 211 |
| N. Hayashi, T. Ueno, H. Shiraishi, T. Nishida, M. Toriumi, and S. Nonogaki | |
| 19. Intensity Dependence in Polymer Photochemistry | 224 |
| James R. Sheats and John S. Hargreaves | |
| 20. Effects of Additives on Positive Photoresist Development | 237 |
| R. C. Daly, T. DoMinh, R. A. Arcus, and M. J. Hanrahan | |
| 21. Importance of the Interface Condition upon Photoresist Image Adhesion in Microelectronic Device Fabrication | 250 |
| J. N. Helbert and N. C. Saha | |
| 22. Polymer Processing to Thin Films for Microelectronic Applications | 261 |
| Samson A. Jenekhe | |
| 23. Stress-Dependent Solvent Removal in Poly(amic acid) Coatings | 270 |
| C. L. Bauer and R. J. Farris | |
| 24. Adhesion and Yield of Polyacrylate-Based Photoresist Lamination in Printed-Circuit Fabrication: Influence of Substrate Thickness and Preheat Treatment | 279 |
| Eric S. W. Kong | |
| 25. Simulation of Resist Profiles for 0.5-μm Photolithography at 248 nm | 292 |
| R. K. Watts, T. M. Wolf, L. E. Stillwagon, and M. Y. Hellman | |

ETCH RESISTANCE OF POLYMERS
IN PLASMA ENVIRONMENTS

| | |
|--|------------|
| 26. Inorganic Resist for Bilayer Applications | 309 |
| Akira Yoshikawa and Yasushi Utsugi | |
| 27. Enhancement of Dry-Etch Resistance of Poly(butene-1 sulfone) | 317 |
| William M. Mansfield | |
| 28. Degradation and Passivation of Poly(alkenylsilane sulfone)s in Oxygen Plasmas | 334 |
| A. S. Gozdz, D. Dijkkamp, R. Schubert, X. D. Wu, C. Klausner, and Murrae J. Bowden | |

29. **A Single-Layer, Multilevel Resist: Limited-Penetration Electron-Beam Lithography**.....350
S. A. MacDonald, L. A. Pederson, A. M. Patlach, and C. G. Willson
30. **Oxygen Ion Etching Resistance of Organosilicon Polymers**.....358
H. Gokan, Y. Saitome, K. Saigo, F. Watanabe, and Y. Ohnishi

POLYMERS IN PHOTONIC APPLICATIONS
AND DEVELOPMENTS

31. **Nonlinear Excitations and Nonlinear Phenomena in Conductive Polymers**.....372
A. J. Heeger, D. Moses, and M. Sinclair
32. **Dipolar Alignment for Second Harmonic Generation: Host-Guest Inclusion Compounds**.....381
David F. Eaton, Albert G. Anderson, Wilson Tam, and Ying Wang
33. **Polymers for Integrated Optics**.....401
John E. Sohn, Kenneth D. Singer, and Mark G. Kuzyk
34. **Polymer Materials for Optical Fiber Coating**.....410
L. L. Blyler, Jr., F. V. DiMarcello, A. C. Hart, and R. G. Huff
35. **Oriented Polymers Obtained by UV Polymerization of Oriented Low Molecular Weight Species**.....417
D. J. Broer and G. N. Mol

HIGH-TEMPERATURE POLYMERS
FOR DIELECTRIC APPLICATIONS

36. **Polyimides in Microelectronics**.....428
Stephen D. Senturia
37. **Soluble Aromatic Polyimides for Film and Coating Applications**.....437
Anne K. St. Clair and Terry L. St. Clair
38. **Cocyclotrimerization of Aryl Acetylenes: Substituent Effects on Reaction Rate**.....445
Daniel J. Dawson, Janice D. Frazier, Phillip J. Brock, and Robert J. Twieg
39. **Photo-Cross-Linking and Imidization of Poly(amic acid) Methacrylate Esters**.....457
H. Ahne, W.-D. Domke, R. Rubner, and M. Schreyer
40. **Polyimides as Interlayer Dielectrics for High-Performance Interconnections of Integrated Circuits**.....466
Ronald J. Jensen
41. **Preparation of Polyimide Mono- and Multilayer Films**.....484
Masa-aki Kakimoto, Masa-aki Suzuki, Yoshio Imai, Mitsumasa Iwamoto, and Taro Hino

POLYMERS FOR ELECTRONICS PACKAGING
AND INTERCONNECTION

42. **Prediction of Lay-Up Consolidation During the Lamination of Epoxy Prepregs**.....499
H. M. Tong and A. S. Sangani

| | |
|--|------------|
| 43. Effect of Room-Temperature-Vulcanized Silicone Cure in Device Packaging..... | 511 |
| Ching-Ping Wong | |
| 44. Evolution of Epoxy Encapsulation Compounds for Integrated Circuits: A User's Perspective..... | 521 |
| H. J. Moltzan, G. A. Bednarz, and C. T. Baker | |
| 45. Stress Analysis of the Silicon Chip-Plastic Encapsulant Interface..... | 537 |
| S. Oizumi, N. Imamura, H. Tabata, and H. Suzuki | |
| 46. Patterning of Fine Via Holes in Polyimide by an Oxygen Reactive Ion Etching Method..... | 547 |
| Hiroshi Suzuki, Hiroyoshi Sekine, Shigeru Koibuchi, Hidetaka Sato, and Daisuke Makino | |
| CONDUCTING POLYMERS | |
| 47. Electrochemical Synthesis and Characterization of New Polyheterocycles..... | 559 |
| M. Aldissi and A. M. Nyitray | |
| 48. Synthesis and Electronic Properties of Poly(8-methyl-2,3-6,7-quinolino) and Its Intermediate..... | 568 |
| J. Z. Ruan and M. H. Litt | |
| 49. From Pyropolymers to Low-Dimensional Graphites..... | 584 |
| S. Yoshimura, M. Murakami, and H. Yasujima | |
| 50. Band-Structure Calculations on Polymeric Chains..... | 600 |
| William J. Welsh | |
| Author Index..... | 612 |
| Affiliation Index..... | 613 |
| Subject Index..... | 614 |

FUNDAMENTALS IN RADIATION CHEMISTRY OF POLYMERS

FUNDAMENTALS IN RADIATION CHEMISTRY OF POLYMERS

The history of radiation chemistry effectively started in 1896 with the discovery of X-rays by Roentgen, and of natural radiation by Becquerel. However, it was not until the advent of nuclear fission on a large scale for power generation (and military purposes) in the 1950s that progress in radiation chemistry really began to be made. The nuclear industry has needed increasing knowledge of the radiation chemistry of materials. Also, there has been a strong incentive to discover new industrial processes which could use the radiation available from reactors. The manufacture of electron accelerators has had an important influence on fundamental research in radiation chemistry and has led to a variety of commercial radiation processes. Chemists have utilized these radiation sources to learn more about the production of reactive species and the mechanisms of chemical reactions initiated by radiation.

The term "radiation" can be used to describe all regions of the electromagnetic spectrum, from radiowaves with wavelengths of meters to gamma rays with wavelengths of nm. Particulate radiations, such as electrons and alpha particles, also have equivalent wavelengths which vary with their energies.

The importance of the radiation chemistry of polymers stems from the large changes in physical and mechanical properties that can be produced by small amounts of radiation. Only a few scissions or crosslinks per molecule, for example, can dramatically affect the strength or solubility of a polymer molecule.

Traditionally, radiation chemistry and photochemistry have been considered as distinct phenomena, being differentiated according to the energy of the photon or particle and the chemistry which follows the initial absorption event. Radiation chemistry derived from photon energies capable of ionizing the parent molecule, whereas photochemistry corresponded to processes resulting from excitation of specific groups in the molecule. However, increasing interest in deep UV radiation for microlithography, the manufacture of excimer lasers producing high intensities of radiation in this special region, and the use of very low energy electron beams in order to maximize absorption in thin films have led to blurring of this boundary.

Radiation must be absorbed before it can produce chemical changes. The initial or primary chemical species resulting from the absorption of high-energy radiation consist of excited states, ions and radicals. Complex sequences of chemical reactions then follow, leading to permanent chemical changes in the molecular structure of the parent molecule. It is these chemical changes that cause the properties of polymers to be modified forming the basis of a variety of applications, e.g., resists for microlithography and graft copolymerization. Such processes can also lead to deterioration of polymers and failure in mechanical applications. This sequence of events is illustrated in Figure 1.

The way in which energy is deposited in a material depends upon the energy of the incident radiation. UV radiation is absorbed selectively by chromophores, whereas high-energy radiation is absorbed according to the electron density of the material. However, energy and charge can migrate after the initial absorption event and the chemical reactions frequently end up being determined by relative bond strengths in the molecule for both types of radiation.

Fundamental studies of the radiation chemistry of polymers can be divided into investigations of (1) permanent chemical changes, including chain scission and crosslinking, structural changes in the polymer, and the formation of small, molecular products, and (2) transient intermediates in the sequence of chemical reactions which follow the absorption event,

especially the formation and disappearance of the initial excited states, ions, and radicals. Pulse radiolysis using microsecond and nanosecond pulses of electrons with energies from 1-10 MeV has contributed greatly to knowledge of these intermediate species. Lasers have been used to provide pulses of UV radiation and for analysis. Studies of polymers in solution in various solvents have been compared with small molecules in the liquid phase and with polymers in the solid state. Studies such as these are providing us with an understanding of the relationships between the molecular structures of polymers and their radiation sensitivity/resistance.

It is important to recognize that fundamental research provides the foundation for technological developments. An understanding of the effects of radiation on polymers, for example, paved the way for the latter's utilization in the electronics industry today in the fabrication of integrated circuits, where polymers sensitive to UV light, electrons, X-rays, and ions are used as resists in lithographic processes. Such technological applications of the radiation chemistry of polymers are increasingly dependent on an inter-disciplinary approach to the development of new processes. Fundamental understanding of the radiation chemistry must be linked with a thorough knowledge of polymer chemistry. However, knowledge of chemistry alone is insufficient since polymers are used mainly in the solid state with all the implications of morphology on properties which is the province of materials science. Finally, any commercial process depends on the contribution of the engineer to convert a laboratory reaction up to an industrial scale. This cooperative approach is illustrated in Fig. 2 and is particularly important in utilizing radiation chemistry in the electronics field.

The following series of papers provides an overview of the fundamental chemistry of radiation-induced changes in polymers with special consideration of electronics applications. Such studies provide valuable insight into the chemical reactions that follow absorption of radiation, an understanding of which may provide the key to improving existing processes, perhaps even to developing new resist mechanisms.

James H. O'Donnell
Polymer and Radiation Group
Department of Chemistry
University of Queensland
Brisbane 4067, Australia

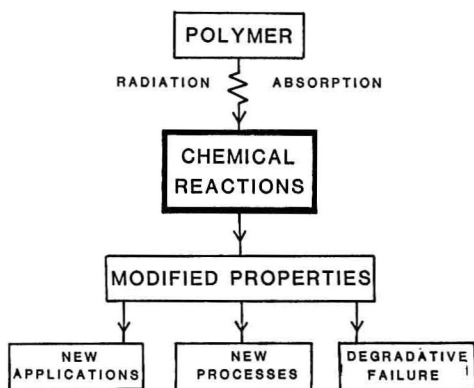


Fig. 1. The sequence of events from the absorption of radiation to its practical applications.

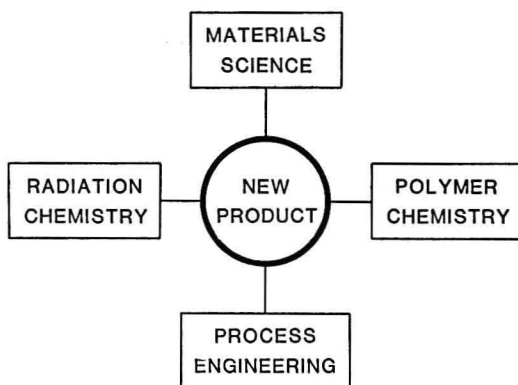


Fig. 2. Schematic representation of the cooperation necessary to utilize radiation chemistry in new technology.

Chapter 1

Development of Radiation Chemistry

G. Arthur Salmon

Cookridge Radiation Research Centre, Cookridge Hospital, University of Leeds,
Leeds, LS16 6QB, United Kingdom

The scientific development of radiation chemistry is reviewed from the discovery in 1895 of x-rays and radioactivity by Roentgen and Becquerel through to the present.

The purpose of this article is to review the development of radiation chemistry which began with the discovery of x-rays by Roentgen(1) in 1895 and shortly afterwards of radioactivity by Becquerel(2), which in both cases involved the observation of chemical change in photographic plates and luminescence in certain phosphors. Clearly, in the space available, the review will be restricted and subjective, but will, it is hoped, give the general framework in which the subject has developed.

The Early Years

Very early studies of these radiations by the discoverers and by the Curies, Rutherford and others demonstrated that they were able to ionize the molecules of a gas upon which they acted. Indeed by 1900, the three kinds of rays, α , β and γ -rays, emitted by radioactive materials were characterised by their charges and their differing abilities to penetrate and ionize materials. Also, shortly after the discovery of radioactivity Pierre and Marie Curie(3) reported that radiation caused the coloration of glass and the formation of ozone from oxygen. Other chemical effects of radiation were quickly discovered. For example, Giesel(1900(4)) showed that radiation coloured alkali halides and decomposed water. Becquerel(1901(5)) showed that β - and γ -rays can induce many of the reactions that were known to be caused by absorption of light, such as the conversion of white to red phosphorus and the decomposition of hydriodic acid solutions. Jorissen and Woudstra(1912(6)) showed that the penetrating radiation from radium caused the coagulation of some colloidal solutions and Jorissen and Ringer(1906(7)) demonstrated that hydrogen and chlorine combine at room temperature under the action of these rays. Thus, during the first decade of this century the basic physical properties of ionizing radiations had been established as well as their ability to bring about chemical change.

0097-6156/87/0346-0005\$06.00/0
© 1987 American Chemical Society