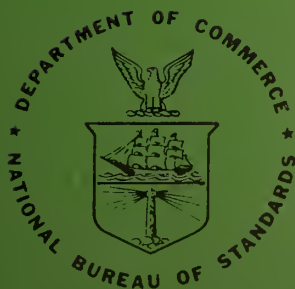


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TECHNICAL NOTE

465

Measurement of Carrier Lifetime in Semiconductors— An Annotated Bibliography Covering the Period 1949-1967



U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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UNITED STATES DEPARTMENT OF COMMERCE
C. R. Smith, Secretary
NATIONAL BUREAU OF STANDARDS • A. V. Astin, Director



TECHNICAL NOTE 465

ISSUED NOVEMBER 1968

Measurement of Carrier Lifetime in Semiconductors—An Annotated Bibliography Covering the Period 1949-1967

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Measurement of Carrier Lifetime in Semiconductors -
An Annotated Bibliography Covering the Period 1949-1967

W. Murray Bullis

About 300 papers concerned with the measurement and interpretation of carrier lifetime in semiconductors are listed together with key words and a brief comment for each. Eight types of entries are included: Description of Methods, Analysis of Results, Standard Methods, Experimental Results, Theoretical Models, Auxiliary Procedures and Data, Reviews, and Books. Emphasis is placed on methods of carrying out measurements of carrier lifetime. Hence complete coverage was attempted and nearly two thirds of the entries appear in the first three categories. A large fraction of the papers listed describe the photoconductivity or photoconductive decay methods. The other most popular methods are based on diode characteristics or the photomagnetolectric effect. In all, 35 methods for measuring carrier lifetime are represented by entries. In addition, representative papers which describe various models for recombination are included together with a number of papers which discuss the influence of surface recombination and trapping phenomena. Auxiliary procedures such as surface preparation, formation of ohmic contacts, control of temperature, and the like are described in some of the entries. Two indexes, a Key Word Index and an Author Index, are provided together with a classification of the various methods for measuring carrier lifetime.

Key Words: bibliography; diffusion length; diode recovery; excess carrier lifetime; measurement methods; photoconductive decay; photoconductivity; photomagnetolectric effect; recombination of excess carriers; semiconductors; surface photovoltage.

1. Introduction

Minority carrier lifetime is a material parameter of fundamental interest in the operation of many semiconductor devices including transistors, switching diodes, radiation detectors, and solar cells. As a result, considerable effort has been expended in the development of methods for measuring lifetime and in the interpretation of the results of the measurement.

This bibliography is primarily concerned with methods for measuring lifetimes of excess carriers in semiconductors. It is the result of a survey of the literature on lifetime measurement which has appeared during the past 20 years. In addition to papers describing the procedures and analyses appropriate to various methods, a selection of papers which cover theoretical models of the recombination process, experimental applications of some of the methods, and auxiliary procedures and information are listed. Several review articles and books which treat various aspects of excess carrier behavior are also included. Reference is made to both forms of the standard procedure for the determination of carrier lifetime by the method of photoconductivity decay.

The methods which are included in the bibliography are listed in Table I. These methods are classified, somewhat arbitrarily, into seven groups.

The first of these contains the conductivity decay methods which, by far, are the most widely utilized methods for evaluating the carrier lifetime of commercially used materials. In these methods the conductivity of a specimen is increased by excess carriers which have been produced in some manner, and the ensuing decay of this excess carrier population is observed by measuring the conductivity after the production of excess carriers is abruptly terminated. In the most familiar form (photoconductive decay), the excess carrier population is produced by a pulse of light with a turn-off time much shorter than the lifetime to be measured. The photoconductive decay time can be determined from direct observation of the specimen resistance as recommended in the standard methods issued by both the American Society for Testing and Materials and the Institute of Electrical and Electronics Engineers or by other less widely used techniques. A fundamental limitation of conductivity

TABLE I. METHODS OF MEASURING CARRIER LIFETIME

Conductivity Decay Methods:

1. Photoconductive Decay
 - Direct Observation of Resistivity
 - Q Changes
 - Microwave Reflection
 - Microwave Absorption
 - Spreading Resistance
 - Eddy Current Losses
2. Pulse Decay
 - Direct Observation of Resistivity
 - Microwave Absorption
3. Bombardment Decay

Conductivity Modulation Methods:

4. Photoconductivity
 - Steady State
 - Modulated Source
 - Infrared Detection, Steady State
 - Infrared Detection, Modulated Source
 - Q Changes
 - Microwave Absorption
 - Eddy Current Losses
 - Spreading Resistance, Modulated Source
5. Pulse Injection-Spreading Resistance

Magnetic Field Methods:

6. Suhl Effect (and Related Effects)
7. Photomagnetoelectric Effect
 - Steady State
 - Modulated Source
 - Transient Decay

Diffusion Length Methods:

8. Travelling Spot
 - Steady State
 - Modulated Source
9. Flying Spot
10. Dark Spot
11. Sweep-Out Effects
 - Pulse Injection
 - Photoinjection
12. Drift Field
13. Pulse Delay
14. Emitter Point Efficiency

Junction Methods:

15. Open Circuit Voltage Decay
16. Reverse Recovery
17. Reverse Current Decay
18. Diffusion Capacitance
19. Junction Photocurrent
 - Steady State
 - Decay
20. Junction Photovoltage
21. Stored Charge
22. Current Distortion Effects
23. Current-Voltage Characteristics

Transistor Methods:

24. Base Transport
25. Collector Response
26. Alpha Cut-Off Frequency
27. Beta Cut-Off Frequency

Other Methods:

28. MOS Capacitance
29. Charge Collection Efficiency
30. Noise
31. Surface Photovoltage
 - Steady State
 - Decay
32. Bulk Photovoltage
 - Steady State
 - Modulated Source
33. Electroluminescence
34. Photoluminescence
35. Cathodoluminescence

decay methods is that they do not yield a value for minority carrier lifetime under conditions where trapping is significant.

Another widely used method involves the observation of the change in conductivity while excess carrier pairs are being generated. Again, most often the excess carrier population is induced by light, and one observes either the magnitude of the steady-state photoconductance or the phase dependence of the photoconductance on the modulation frequency of the illumination. In the presence of trapping, the response is frequently dominated by the lifetime of the majority carrier.

Two methods of more limited application are based on the deflection of injected carriers by a magnetic field. One of these, the photomagnetoelectric effect in which the excess carriers are generated optically, has been widely used for research purposes and typical results have been reported on many semiconductors. It is not in general use as an evaluation method because of the complexities introduced by the magnetic field, the need to determine the intensity of the illuminating light, and, in the case of silicon, the presence of background signals arising from nonuniform surface or bulk recombination which tend to obscure the desired signal. The main advantages of this method are that it yields a value for lifetime of the minority carrier in the presence of trapping and that it may be combined readily with a measurement of photoconductivity so that both lifetimes can be determined. In the Suhl effect, excess carriers injected at a point contact are deflected by the magnetic field. In related effects, equilibrium carriers under the influence of crossed electric and magnetic fields are deflected similarly. These effects are useful for determination of lifetime only in near-intrinsic specimens with surfaces which have different recombination characteristics.

A variety of injection and detection techniques can be used to determine carrier lifetime indirectly through measurement of carrier diffusion length (the square root of the product of lifetime and diffusion coefficient). One of these methods, the travelling spot method, enjoyed considerable popularity for a time but no longer appears to be in widespread use.

Several other methods involve the use of a p-n junction either biased in the forward direction for injection of excess carriers or biased in the reverse direction

for the separation of electrons and holes. The most widely used of these are the recovery time of the reverse current or the decay of the open-circuit voltage following a forward pulse. In addition, the junction photovoltage method is quite useful, particularly when gamma-ray excitation is employed.

Measurements on transistor structures are frequently complicated by the interaction of several different phenomena. Nevertheless methods based on base transport time seem to predominate.

The remaining methods are arbitrarily grouped together. Of these, the method based on the spectral dependence of the steady-state surface photovoltage seems to yield the most direct measure of carrier lifetime through a measurement of the diffusion length.

Analysis of the results of lifetime measurement often requires the use of a model for carrier recombination. A selection of papers which describe recombination models such as radiative recombination, pair recombination, the Auger effect, and recombination through Shockley-Read-Hall centers is listed. In addition, a number of papers which discuss the influence of surface recombination, trapping effects, and multiple recombination levels are included.

Frequently auxiliary procedures or data are desirable or necessary to carry out the measurement of carrier lifetime. Papers which indicate methods for treating surfaces (particularly to obtain low surface recombination), for obtaining ohmic or injecting contacts, for shaping specimens, for controlling temperature, for measuring photon flux density, and for obtaining light sources with short turn-off time are included in the bibliography together with several papers which give values of absorption coefficient as a function of wavelength in the region of the band edge.

Sources for the bibliography were personal files, subject indexes of *Science Abstracts* since 1956, literature citations in papers collected, and current journal issues not yet abstracted. Although an attempt at completeness was made in collecting papers which describe a particular method or its analysis, it is almost certain that some papers have been overlooked. The compiler would appreciate having users of the bibliography direct his attention to any such omissions. It should be emphasized that no attempt was made at completeness in the collection of papers on models, applications, or auxiliary procedures.

2. Organization and Use of the Bibliography

Each paper has been given an identification code which consists of a sequence of two digits, a letter, and another digit. The first two digits indicate the year of publication and the letter is the initial of the first author's surname. The last digit is used to distinguish those papers which would otherwise have the same code. No rule was used in the assignment of the last digit.

The entries in the bibliography are arranged according to their codes. The codes are grouped first by year, then in alphabetical order by letter, and then in numerical order by the last digit. Each reference citation in the bibliography consists of the author(s), title, and source followed by an abstract identification code in parentheses, if one was available. The code begins with either PA, EA, or CA to indicate that the abstract may be found in *Series A, Physics, of Science Abstracts*; *Series B, Electrical and Electronics* (formerly *Electrical Engineering*) of *Science Abstracts*; or *Chemical Abstracts*, respectively. Following these letters are two digits which indicate the year the paper was abstracted.

The remainder of the abstract code consists of the abstract number in the case of abstracts appearing in *Science Abstracts* or the volume number, column number, and location letter in the case of abstracts appearing in *Chemical Abstracts*. Journal abbreviations generally follow those of *Science Abstracts*. Exceptions were made in the cases of publications of the Institution of Electrical Engineers (London), which is abbreviated IEE, and publications of the Institute of Electrical and Electronics Engineers and its predecessor, the Institute of Radio Engineers, which are abbreviated IEEE and IRE, respectively. For those publications which are not listed in *Science Abstracts* no abbreviations were made where confusion might arise.

If the reference citation is followed by a number preceded by the letters AD, the paper may be obtained from the Clearinghouse for Federal Scientific and Technical Infor-

mation (CFSTI), Department of Commerce, Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151, by using the AD number.

English is the language of the papers unless otherwise noted. When foreign language papers appear in journals which are regularly translated into English only the translated reference is cited. The code number assigned to translated papers refers to the year of publication in the original language and thus may be different from the year cited.

Special translations are noted together with the citation to the original journal article. For those special translations which are available from CFSTI the AD number is listed. Translations of some papers in languages other than English, French, or German could not be located. The listings for such papers, which are marked with a star (*) before the title, are based on the English language abstract.

The contents and approach of each entry are indicated by key words grouped into six major categories: (1) type of entry, (2) method of measurement, (3) experimental technique, (4) range (in microseconds), (5) auxiliary procedures and data, and (6) model for recombination. The key words are listed by category in the Key Word Index which also lists the code number for each citation with the key word. In each entry, the key words are listed, one category per line, below the reference in the order they appear in the Key Word Index.

Following the key word listing, the entries contain a brief comment concerning the principal features of pertinence to the subject of the bibliography. In most cases, information given in the title or key word listing is not duplicated. Some foreign language papers marked with a star have no such comments since the abstract did not give sufficient information.

A complete Author Index is also provided.

The material for this critical bibliography was collected between 23 November 1966 and 31 December 1967 as part of a project supported under USAF Delivery Order F33615-67-M-5007. The work was monitored for the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433, by R. L. Hickmott under Task 737102 "Semiconductor Materials."

The author wishes to acknowledge the contributions of Mrs. Susan Needham who found and collected most of the material, Miss Juanita Seal who assisted during the intermediate stages of preparation, and Mrs. Pat Smith who typed the final manuscript. Particular thanks are due to Harry A. Schafft (whose earlier efforts on similar bibliographic collections much simplified the preparation of this one for his assistance with both format and the selection of key words.

3. Key Word Index

Type of Entry

METHOD, Description of

51G1, 51H1, 52N1, 52V1, 53H1, 53M1, 53P1, 54A1, 54G1, 54M1,
55D1, 55G1, 55L1, 55M1, 55S2, 55S3, 56G2, 56H1, 56H2, 56H4,
56W1, 56W2, 57A1, 57D1, 57E2, 57G1, 57J1, 57S4, 58B2, 58B8,
58G2, 58H2, 58K1, 59A2, 59D1, 59K1, 59K2, 59R1, 59R2, 59W2,
60B3, 60D1, 60J1, 60L1, 60O1, 60Q1, 60S1, 60S2, 61D1, 61G1,
61H1, 61L2, 61M2, 61M3, 61W1, 62A1, 62B3, 62C1, 62D1, 62K2,
62N1, 62S2, 62Z1, 63C1, 63D1, 63D2, 63F2, 63H1, 63J1, 63W1,
64A1, 64B3, 64B4, 64G3, 64H1, 64J1, 64M1, 64S3, 65B1, 65C1,
65E2, 65H1, 65L1, 65M1, 65M4, 65S1, 65S3, 65S5, 65V2, 66C1,
66C3, 66G1, 66H1, 66J1, 66K1, 66M2, 66P1, 66T2, 66Z1, 67B1,
67D1, 67H1, 67H2, 67L1, 67M1, 67M2, 67W1

ANALYSIS

49S1, 49S2, 53G1, 54K1, 54L1, 55A3, 55H1, 55S1, 55V1, 56A1,
56A2, 56D1, 56H3, 56S1, 56V1, 57B2, 57C1, 57H1, 57I1, 57S1,
57V1, 57V2, 58G1, 58L1, 58M1, 58N1, 58R1, 58S3, 58Z1, 59A1,
59B2, 59G1, 59H2, 59M1, 59M2, 59O1, 59S1, 59W1, 60A1, 60B1,
60G2, 60G3, 60G4, 60R1, 60R2, 60S3, 60S4, 60V1, 60V2, 61A1,
61B1, 61B2, 61F1, 61J1, 61K1, 61M1, 61N1, 61R1, 62B1, 62K1,
62M1, 62P1, 62R1, 63B2, 63F1, 63S1, 63T2, 64B1, 64G1, 64G2,
64H2, 64I4, 64N1, 64P2, 64S1, 65B2, 65B3, 65M3, 66C2, 66D1,
66K2, 66S1, 66T1, 66W1

STANDARD

61I1, 66A2

EXPERIMENTAL Application

53H2, 53H3, 53S1, 54M2, 55A1, 55H2, 55H3, 55P1, 56E1, 56K1,
57B1, 57I2, 57P1, 57R1, 57S3, 58B3, 58B6, 58H1, 58H3, 58S2,
59B3, 59D2, 59H1, 60B2, 60D2, 60G1, 60L2, 60P1, 61H2, 61H3,
61H4, 61L1, 61P1, 61P3, 61R2, 61V1, 62R2, 62V2, 63K1, 63T1,
63Z1, 64B2, 64D1, 64F1, 64I1, 64I2, 64I3, 64P1, 64S2, 64V1,
65K1, 65M2, 65N1, 65S2, 65S4, 65V1, 66F1, 66I1, 66I2, 66K3,
66M1, 66O1, 66S2, 67E1, 67W2

PROCEDURE, Auxiliary

57E1, 57G3, 58B1, 58B7, 59H3, 60W1, 62B2, 62H1

MODEL, Theoretical

52H1, 52S1, 54V1, 56K2, 56L1, 57G2, 57L1, 57S2, 58B4, 58S1,
58W1, 59B1, 62H2, 62V1, 65E1, 66A1

REVIEW

54A2, 55A2, 56G1, 57R2, 58A1, 58B5, 58M2, 58V1, 61P2, 62S1,
63B1

BOOK

50S1, 60B4, 62B4, 62T1, 63R1, 64R1

Method of Measurement

PCD (Photoconductive Decay-Direct Observation)

Method: 55S3, 56H4, 56W2, 57A1, 57D1, 58B8, 64G3, 65M1,
66G1, 66P1

Analysis: 56H3, 57C1, 57S1, 58M1, 58N1, 58R1, 58S3, 59M1,
59O1, 59S1, 60B1, 60R2, 60V1, 60V2, 61B2, 61F1,
61N1, 64S1, 66S1

Standard: 61I1, 66A2

Experimental: 53H2, 55H2, 55H3, 58B3, 58S2, 60P1, 61H3,
61V1, 66I1, 66I2

Procedure: 57G3

Review: 55A2, 58B5, 58V1, 62S1

Book: 50S1, 62B4, 64R1

PCD-Q (Photoconductive Decay-Q Changes)

Method: 59K2, 61W1, 62N1, 65E2, 67M2

PCD-MICROWAVE REFLECTION

Method: 62D1, 63J1

Review: 63B1

PCD-MICROWAVE ABSORPTION

Method: 59R1, 60D1, 60L1, 63J1

Analysis: 60A1, 61A1, 61J1, 63T2, 64H2

Review: 62S1, 63B1

PCD-SPREADING RESISTANCE

Method: 63W1
Experimental: 63Z1

PCD-EDDY (Photoconductive Decay-Eddy Current Losses)

Method: 67L1

PULSE DECAY (Direct Observation)

Method: 52N1, 54M1
Analysis: 56A1
Experimental: 54M2
Review: 54A2, 55A2, 58B5, 58V1, 62S1

PULSE DECAY - MICROWAVE (Absorption)

Method: 59R1
Analysis: 60A1, 61A1, 61J1, 63T2
Review: 62S1

BOMBARDMENT DECAY

Method: 56W1, 62B3, 65C1
Experimental: 62V1, 64V1

PC (Steady State Photoconductivity)

Method: 56G2, 57G1, 58B2, 58K1, 60S2, 61L2, 63F2, 64S3,
65B1, 67D1
Analysis: 56D1, 57C1, 58Z1, 59A1, 59B2, 59M2, 60G2, 60V1,
60V2, 61R1, 62P1, 62R1, 63S1, 64B1, 65B2
Experimental: 56K1, 57B1, 58B6, 59H1, 60B2, 60G1, 60L2,
61H2, 61H3, 61P1, 64S2, 65V1
Review: 61P2, 62S1
Book: 60B4, 62B4, 62T1, 63R1, 64R1

PC(M) (Photoconductivity-Modulated Source)

Method: 54G1, 58H2, 59K1, 59R2, 61M2, 62C1, 65S1, 66P1,
66Z1
Analysis: 55S1, 57V1, 58G1, 58L1, 61B1, 64G2, 66W1
Experimental: 61R2
Procedure: 57E2, 60W1

PC-IR (Photoconductivity-Infrared Detection)

Method: 56H1

Review: 62S1

PC(M)-IR (Photoconductivity-Modulated Source, Infrared Detection)

Analysis: 59H2, 64N1

PC-Q (Photoconductivity-Q Changes)

Method: 56H2

PC-MICROWAVE (Photoconductivity-Microwave Absorption)

Method: 60J1

PC-EDDY (Photoconductivity-Eddy Current Losses)

Review: 62S1

PC(M)-SPREADING RESISTANCE

Method: 66H1

SPREADING RESISTANCE (Pulse Injection)

Method: 55S2, 57D1

Analysis: 57I1

Experimental: 57I2, 64P1

Review: 62S1

SUHL EFFECT (and Related Effects)

Method: 53H1, 57S4

Analysis: 49S1

Book: 50S1

PME (Steady State Photomagnetoelectric Effect)

Method: 53M1, 57G1, 58B8, 58K1, 61L2, 63C1, 64S3, 67D1

Analysis: 56V1, 58Z1, 59A1, 59M2, 59W1, 60G3, 60G4, 60R1,
60V1, 60V2, 61R1, 62B1, 62P1, 62R1, 63F1, 63S1,
64B1, 65B2, 66C2, 66K2

Experimental: 56K1, 57B1, 59H1, 60B2, 60G1, 60L2, 61H2,
61H3, 61P1, 63K1, 64I1, 64I2, 64S2, 65M2

Review: 54A2, 56G1, 58B5, 58V1, 61P2, 62S1

Book: 62T1, 64R1

PME(M) (PME Effect-Modulated Source)

Method: 54G1, 59R2, 62Z1
Analysis: 58L1, 64G2, 65B3
Experimental: 61R2
Review: 56G1

PME(T) (Transient PME Effect)

Analysis: 55H1, 59M1
Review: 56G1

TRAVELLING SPOT (Steady Source)

Method: 51G1, 52V1, 55M1, 56G2, 60B3, 61M3, 65H1, 65S5,
66M2, 66T2
Analysis: 56A1, 56H3, 61F1
Experimental: 55A1
Review: 54A2, 55A2, 58B5, 58V1, 62S1

TRAVELLING SPOT (M) (Modulated Source)

Method: 64M1
Analysis: 55A3

FLYING SPOT

Method: 54A1, 64B4
Analysis: 56S1
Review: 58B5, 62S1

DARK SPOT

Method: 60S1, 65S3

PULSE INJECTION-SWEEP OUT

Method: 63H1

PHOTOINJECTION-SWEEP OUT

Method: 57D1

DRIFT FIELD

Method: 51H1, 55D1, 56W2
Analysis: 49S2, 56H3
Review: 54A2, 55A2, 58B5, 58V1, 62S1
Book: 50S1

PULSE DELAY

Method: 55S2, 57D1, 65L1
Review: 62S1

EMITTER POINT EFFICIENCY

Analysis: 49S2
Experimental: 53H3
Review: 55A2
Book: 50S1

VOLTAGE DECAY (Open Circuit)

Method: 55G1, 55L1, 63D1, 67M1
Analysis: 53G1, 56A2, 57H1, 61K1
Experimental: 58H1, 64D1, 65S4, 67W2
Procedure: 62H1

REVERSE RECOVERY

Method: 62K2, 63D2
Analysis: 54K1, 54L1, 57B2, 57H1, 61K1, 61M1, 62K1, 62M1,
64G1, 64I4, 65M3, 66D1
Experimental: 53S1, 57R1, 59B3, 64F1, 65S4, 66F1, 66O1,
67W2
Review: 58V1

REVERSE CURRENT DECAY

Method: 53P1
Analysis: 54K1, 54L1, 57H1, 61K1, 62K1, 62M1
Experimental: 55P1
Review: 62S1

DIFFUSION CAPACITANCE

Method: 59A2, 62A1, 64A1
Experimental: 57P1

JUNCTION PHOTOCURRENT (Steady State)

Method: 58G2, 59W2, 61D1, 64J1
Analysis: 60S3, 60S4, 64P2
Experimental: 57S3, 60D2, 61L1, 62R2, 65N1

JUNCTION PHOTOCURRENT DECAY

Analysis: 61B2, 66T1

JUNCTION PV (Steady-State Junction Photovoltage)

Method: 62S2, 64J1

Book: 62T1

STORED CHARGE

Method: 64H1, 66C1

Experimental: 65S2

DISTORTION (Diode Current)

Method: 67B1

I-V (Diode Current-Voltage Characteristic)

Experimental: 64I3

BASE TRANSPORT (Transistor)

Method: 59D1

Experimental: 56E1, 58H1, 61H4, 64D1, 65S4

COLLECTOR RESPONSE (Transistor)

Experimental: 65S4, 66S2

ALPHA CUT-OFF FREQUENCY

Experimental: 66F1

BETA CUT-OFF FREQUENCY

Experimental: 65S4

MOS CAPACITANCE

Method: 66J1, 67H1, 67H2

CHARGE COLLECTION EFFICIENCY

Method: 66C3

Analysis: 57V2

Experimental: 59D2, 63T1, 66K3, 66M1

NOISE

Method: 6001
Experimental: 58B6, 58H3, 60G1, 61V1, 64B2
Review: 62S1

SPV (Steady-State Surface Photovoltage)

Method: 60Q1, 61G1, 64B3, 65M4, 65V2, 66K1

SPV DECAY

Method: 57J1
Analysis: 59G1
Review: 62S1

BULK PV (Steady-State Bulk Photovoltage)

Analysis: 63B2
Experimental: 65K1, 67E1
Book: 62T1

BULK PV(M) (Bulk Photovoltage-Modulated Source)

Analysis: 58L1

ELECTROLUMINESCENCE

Method: 61H1

PHOTOLUMINESCENCE

Method: 65V2

CATHODOLUMINESCENCE

Method: 67W1

Experimental Technique

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59K1, 59R2, 61B1, 62A1, 62C1, 64A1, 64G2, 66H1, 66P1, 66Z1

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54M1, 55S1, 57A1, 57E2, 58H2, 64M1, 65S1, 66Z1

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65V1, 65V2

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67W1

GAMMA SOURCE

58G2, 62R2

ALPHA SOURCE

59D2, 63T1, 66C3, 66K3

PROTON SOURCE

62R2

X-RAY SOURCE

55M1, 65C1

Range (Microseconds)

>0.0001
64A1, 67H1

0.0001-0.001
62V2

~0.001
62B3, 62K2

0.001-0.1
62A1, 64F1

>0.01
57G3, 59K1, 60P1, 61V1, 62C1

0.01-2
57S3

0.01-10
56W1

>0.02
60W1

0.025-0.25
66C1

<0.1
56K1

0.1-100
62H1

>1
54M1, 66Z1

1-500
52V1

>10
63F2

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57J1, 61I1, 66A2

n-Ge: 51H1, 52N1, 54M2, 57E1, 60B2, 61F1, 61P1, 61P3,
62B2, 63Z1

p-Ge: 54M2, 61P1, 61P3, 62B2, 63Z1

n-Si: 56H3, 58B1, 59D2, 59H3, 61F1, 61P3, 63Z1, 64S2

p-Si: 56H3, 58B1, 59D2, 59H3, 61F1, 61P3, 63Z1, 65M2,
66I2
p-InSb: 56K1

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n-Ge: 51H1, 53H3, 61I1, 66A2
p-Ge: 61I1, 66A2
n-Si: 56W2, 57I2, 61I1, 64S2, 66A2
p-Si: 56W2, 57I2, 61I1, 66A2, 66I1

INJECTING CONTACTS

n-Si: 57I2
p-Si: 57I2

ABSORPTION COEFFICIENT (near band edge)

Ge: 58B7, 61P1, 64B3
Si: 58B7, 60D2, 64B3, 64I2
GaAs: 64B3

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PULSER

62H1

Model for Recombination

S-R-H (Shockley-Read-Hall Single Level Center)

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66W1
Experimental: 55P1, 57R1, 58B3, 58S2, 64V1
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Book: 62B4, 64R1

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Analysis: 59O1, 61R1
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Model: 56K2, 56L1, 57L1, 58B4, 58S1, 58W1
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Book: 62B4, 64R1

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60V2, 61B2, 61N1, 61R1, 62R1, 66S1
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Review: 55A2, 57R2, 58B5, 58M2
Book: 62B4, 63R1, 64R1

PAIR RECOMBINATION

Model: 66A1

BAND-TO-BAND RECOMBINATION

Model: 57L1

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Experimental: 55A1
Model: 54V1
Review: 58R1, 58B5
Book: 62B4, 64R1

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Book: 62B4

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1949 - 1954

- 49S1 Suhl, H., and W. Shockley
CONCENTRATING HOLES AND ELECTRONS BY
MAGNETIC FIELDS
Phys. Rev., vol. 75, pp. 1617-1618,
May 15, 1949. (PA:49-7003)

ANALYSIS

SUHL EFFECT

The deflection of injected carriers by a magnetic field is reported for the first time. The phenomenon was later used for lifetime measurement under specialized conditions. (See 53H1.)

- 49S2 Shockley, W., G. L. Pearson, and
J. R. Haynes
HOLE INJECTION IN GERMANIUM--QUANTI-
TATIVE STUDIES AND FILAMENTARY TRAN-
SISTORS
Bell Syst. Tech. J., vol. 28,
pp. 344-366, July 1949.

ANALYSIS

DRIFT FIELD, EMITTER POINT EFFICIENCY

The drift of injected holes in an electric field is described and analyzed. The relationship between lifetime and the magnitude of the injected pulse after drift is discussed. (See also 50S1, 53H3, 55A2.)

- 50S1 Shockley, W.
ELECTRONS AND HOLES IN SEMICONDUCTORS
D. Van Nostrand, New York, 1950.
(EA:51-4467)

BOOK

PCD, SUHL EFFECT, DRIFT FIELD, EMITTER POINT EFFICIENCY

SURFACE

Although portions of this classic treatise are somewhat dated, it remains the fundamental source of much of the analysis of semiconductor phenomena. In particular, the theory of decay in a filament with finite surface recombination is developed.

- 51G1 Goucher, F. S.
MEASUREMENT OF HOLE DIFFUSION IN n-
TYPE GERMANIUM
Phys. Rev., vol. 81, p. 475, February
1, 1951. (PA:51-4379)

METHOD

TRAVELLING SPOT

The basis for the method is developed briefly. It is of considerable historic interest.

- 51H1 Haynes, J. R., and W. Shockley
THE MOBILITY AND LIFE OF INJECTED
HOLES AND ELECTRONS IN GERMANIUM
Phys. Rev., vol. 81, pp. 835-843,
March 1, 1951. (PA:51-4381)

METHOD

DRIFT FIELD

SURFACE TREATMENT (n-Ge), OHMIC CONTACTS (n-Ge), SPECIMEN SHAPING

Although primarily concerned with mobility measurement, this paper includes a description of the method and a discussion of the influence of surface recombination on the measured value of lifetime.

- 52H1 Hall, R. N.
ELECTRON-HOLE RECOMBINATION IN
GERMANIUM
Phys. Rev., vol. 87, p. 387, July 15,
1952. (PA:52-8184)

MODEL

S-R-H

The classic model for recombination through a discrete impurity center is introduced briefly.

- 52N1 Navon, D., R. Bray, and H. Y. Fan
LIFETIME OF INJECTED CARRIERS IN
GERMANIUM
Proc. IRE, vol. 40, pp. 1343-1347,
November 1952. (PA:53-849)

METHOD

PULSE DECAY

SURFACE TREATMENT (n-Ge)

Details of the time dependence of the decay curves for a variety of conditions are given in this original paper on the method.

- 52S1 Shockley, W., and W. T. Read, Jr.
STATISTICS OF THE RECOMBINATION OF
HOLES AND ELECTRONS
Phys. Rev., vol. 87, pp. 835-842,
September 1, 1952. (PA:52-8183)

MODEL

S-R-H

A thorough analysis of the model for recombination through a discrete impurity center is developed.

52V1 Valdes, L. B.
MEASUREMENT OF MINORITY CARRIER LIFE-
TIME IN GERMANIUM
Proc. IRE, vol. 40, pp. 1420-1423,
November 1952. (PA:53-844)

METHOD
TRAVELLING SPOT
1-500

This is the original publication on a modification of the method which was developed by Morton and Haynes. The illuminated region is a long, thin rectangle rather than a small circle. (Compare 51G1.)

53G1 Gossick, B. R.
POST-INJECTION BARRIER ELECTROMOTIVE
FORCE OF p-n JUNCTIONS
Phys. Rev., vol. 91, pp. 1012-1013,
August 15, 1953. (PA:53-8422)

ANALYSIS
VOLTAGE DECAY

The initial suggestion for this method is more fully developed and described in 55G1.

53H1 Hunter, L. P., E. J. Huibregtse, and
R. L. Anderson
CURRENT CARRIER LIFETIMES DEDUCED FROM
HALL COEFFICIENT AND RESISTIVITY MEAS-
UREMENTS
Phys. Rev., vol. 91, pp. 1315-1320,
September 15, 1953. (PA:54-462)

METHOD
SUHL EFFECT

An unusual method based on the Suhl and Hall effects and suitable only for intrinsic or near-intrinsic specimens is described.

53H2 Haynes, J. R., and J. A. Hornbeck
TEMPORARY TRAPS IN SILICON AND
GERMANIUM
Phys. Rev., vol. 90, pp. 152-153,
April 1, 1953. (PA:53-4803)

EXPERIMENTAL
PCD
TRAPPING

This initial report of trapping in silicon at room temperature and in germanium at lower temperature is primarily of historic interest.

53H3 Hogarth, C. A.
A STUDY OF CARRIER INJECTING PROPER-
TIES OF EMITTER CONTACTS AND LIGHT
SPOTS AT NORMAL AND MODERATELY
ELEVATED TEMPERATURES
Proc. Phys. Soc., vol. B66, pp. 845-
858, October 1953. (PA:54-1315)

EXPERIMENTAL
EMITTER POINT EFFICIENCY
OHMIC CONTACTS (n-Ge), HIGH TEMPERATURE
Experimental conditions appropriate to
the use of this method are given in detail.

53M1 Moss, T. S., L. Pincherle, and
A. M. Woodward
PHOTOELECTROMAGNETIC AND PHOTO-
DIFFUSION EFFECTS IN GERMANIUM
Proc. Phys. Soc., vol. B66, pp. 743-
752, September 1953. (PA:54-472)

METHOD
PME

This early description and analysis of the PME effect contains some simplifications which have subsequently proved to be invalid. (See e.g. 56V1.)

53P1 Pell, E. M.
RECOMBINATION RATE IN GERMANIUM
BY OBSERVATION OF PULSED REVERSE
CHARACTERISTIC
Phys. Rev., vol. 90, pp. 278-279,
April 15, 1953. (PA:53-4091)

METHOD
REVERSE CURRENT DECAY

The current decay following abrupt reversal of the potential across a diode is analyzed in terms of the lifetime of minority carriers. The relationship between recovery time and lifetime can be obtained from the analysis but it is not given explicitly.

53S1 Shulman, G., and M. E. McMahon
RECOVERY CURRENTS IN GERMANIUM p-n
JUNCTION DIODES
J. Appl. Phys., vol. 24, pp. 1267-
1272, October 1953. (PA:54-1311)

EXPERIMENTAL
REVERSE RECOVERY

Use of the effect for lifetime measurements is not considered in this early paper on reverse recovery which is primarily of historical interest.

54A1 Adam, G.
A FLYING LIGHT SPOT METHOD FOR SIMULTANEOUS DETERMINATION OF LIFETIME AND MOBILITY OF INJECTED CURRENT CARRIERS
Physica, vol. 20, pp. 1037-1041,
November 1954. (PA:55-3733)

METHOD

FLYING SPOT

This modification of the travelling spot technique for diffusion length measurement enables separation of the lifetime and mobility factors.

54A2 Aigrain, P.
MEASUREMENT OF MINORITY CARRIER LIFETIME IN SEMICONDUCTORS (In French)
Ann. Radioelect., vol. 9, pp. 219-226,
July 1954. (PA:55-1808)

REVIEW

PULSE DECAY, PME, TRAVELLING SPOT, DRIFT FIELD

A brief review of several methods is followed by a detailed description of the PME method. A discussion of the problems and advantages of the PME method leads to a recommendation for its use.

54G1 Grosvalet, J.
THE PHOTOMAGNETOELECTRIC EFFECT FOR SINUSOIDAL CONDITIONS IN SEMICONDUCTORS. APPLICATION TO THE MEASUREMENT OF MINORITY CARRIER LIFETIME. (In French)
Ann. Radioelect., vol. 9, pp. 360-365,
October 1954. (PA:55-1809)

METHOD

PC(M), PME(M)

PHASE SHIFT

The magnitude of the phase shift between the PME and PC voltages under sinusoidal excitation is shown to be directly related to the minority carrier lifetime (in the absence of trapping). A description of the method is given in English in 56G1.

54K1 Kingston, R. H.
SWITCHING TIME IN JUNCTION DIODES AND JUNCTION TRANSISTORS
Proc. IRE, vol. 42, pp. 829,834,
May 1954. (EA:54-3525)

ANALYSIS

REVERSE RECOVERY, REVERSE CURRENT DECAY

A more rigorous mathematical treatment may be found elsewhere (see 54L1) but the basic analysis of the method in the present paper is adequate for most cases. Extension to arbitrary base widths may be found in 57B2.

54L1 Lax, B., and S. F. Neustadter
TRANSIENT RESPONSE OF A p-n JUNCTION
J. Appl. Phys., vol. 25, pp. 1148-1154,
September 1954. (PA:55-295)

ANALYSIS

REVERSE RECOVERY, REVERSE CURRENT DECAY

A detailed analysis of the reverse characteristics of an asymmetrical long-base diode is given. (See 54K1 for a generally adequate but less rigorous treatment.)

54M1 Many, A.
MEASUREMENT OF MINORITY CARRIER LIFETIME AND CONTACT INJECTION RATIO ON TRANSISTOR MATERIALS

Proc. Phys. Soc., vol. B67, pp. 9-17,
January 1954. (PA:54-3482)

METHOD

PULSE DECAY

COMPARATOR, BRIDGE

>1

This is the original article on the bridge version of the pulse decay method; the modification is described thoroughly.

54M2 McKelvey, J. P., and R. L. Longini
VOLUME AND SURFACE RECOMBINATION RATES FOR INJECTED CARRIERS IN GERMANIUM
J. Appl. Phys., vol. 25, pp. 634-641,
May 1954. (PA:54-7416)

EXPERIMENTAL

PULSE DECAY

SURFACE TREATMENT (n-Ge, p-Ge)

A thorough analysis of the method is presented in addition to values of surface recombination rate on germanium surfaces treated with a variety of etchants.

54V1 Van Roosbroeck, W., and W. Shockley
PHOTON-RADIATIVE RECOMBINATION OF ELECTRONS AND HOLES IN GERMANIUM
Phys. Rev., vol. 94, pp. 1558-1560,
June 15, 1954. (PA:54-8281)

MODEL

RADIATIVE RECOMBINATION

The lifetime associated with this recombination mechanism is shown to be significantly longer than the values commonly observed in germanium.

- 55A1 Avery, D. G., and D. P. Jenkins
MEASUREMENTS OF DIFFUSION LENGTH
IN INDIUM ANTIMONIDE
J. Electronics, vol. 1, pp. 145-151,
September 1955. (PA:55-8764)

EXPERIMENTAL
TRAVELLING SPOT
LOW TEMPERATURE
RADIATIVE RECOMBINATION

The discussion of some of the assumptions and difficulties involved in deriving values of lifetime from measurements of diffusion length can be extended to the case of measurements in germanium and silicon.

- 55A2 Arthur, J. B., W. Bardsley, A. F. Gibson, and C. A. Hogarth
ON THE MEASUREMENT OF MINORITY CARRIER LIFETIME IN n-TYPE SILICON
Proc. Phys. Soc., vol. B68, pp. 121-129, March 1955. (PA:55-3774)

REVIEW
PCD, PULSE DECAY, TRAVELLING SPOT, DRIFT FIELD, EMITTER POINT EFFICIENCY TRAPPING

Problems encountered in lifetime measurements on n-type silicon are considered thoroughly. It is concluded that, because of the influence of trapping, the PCD method is not a reliable one. Conditions required for correct measurements by the travelling spot method are considered in detail. (See also 56H3.) The other methods are discussed briefly.

- 55A3 Avery, D. G., and J. B. Gunn
THE USE OF A MODULATED LIGHT SPOT IN SEMICONDUCTOR MEASUREMENTS
Proc. Phys. Soc., vol. B68, pp. 918-921, November 1955. (PA:56-2085)

ANALYSIS
TRAVELLING SPOT (M)
PHASE SHIFT

The theory for the travelling spot method is extended to include modulation of the light. It is shown that both lifetime and diffusion length can be determined if the phase shift is measured in addition to the amplitude.

- 55D1 Durrant, N. F.
MEASUREMENT OF MINORITY CARRIER LIFETIMES IN SEMICONDUCTORS
Proc. Phys. Soc., vol. B68, pp. 562-563, August 1955. (PA:55-8746)

METHOD
DRIFT FIELD

Trapping and conductivity modulation effects are detected as distortion of the collector pulse in this pulsed drift field modification. Elimination of trapping by filling the traps with auxiliary illumination is recommended in this brief note.

- 55G1 Gossick, B. R.
ON THE TRANSIENT BEHAVIOR OF SEMICONDUCTOR RECTIFIERS
J. Appl. Phys., vol. 26, pp. 1356-1365, November 1955. (PA:56-1237)

METHOD
VOLTAGE DECAY

The basis for the method is presented in considerable detail; measuring circuits and apparatus are described.

- 55H1 Hall, L. H.
PHOTODIFFUSION CURRENT HALL EFFECT: TRANSIENT BEHAVIOR
Phys. Rev., vol. 97, pp. 1471-1474, March 15, 1955. (PA:55-4676)

ANALYSIS
PME(T)

The transient PME effect is shown not to be suitable for lifetime measurements.

- 55H2 Hornbeck, J. A., and J. R. Haynes
TRAPPING OF MINORITY CARRIERS IN SILICON. I. p-TYPE SILICON
Phys. Rev., vol. 97, pp. 311-321, June 15, 1955. (PA:55-2750)

EXPERIMENTAL
PCD
TRAPPING

Trapping by two types of centers is demonstrated by both drift mobility and lifetime experiments and their interpretation in this classic paper. (See 55H3 for an extension to n-type silicon.)

- 55H3 Haynes, J. R., and J. A. Hornbeck
TRAPPING OF MINORITY CARRIERS IN SILICON. II. n-TYPE SILICON
Phys. Rev., vol. 100, pp. 606-615, October 15, 1955. (PA:56-351)

EXPERIMENTAL
PCD
TRAPPING

The techniques and methods of 55H2 are extended to n-type silicon.

55L1 Lederhandler, S. R., and L. J. Giacoletto
MEASUREMENT OF MINORITY CARRIER LIFETIME AND SURFACE EFFECTS IN JUNCTION DEVICES
Proc. IRE, vol. 43, pp. 477-483, April 1955. (EA:55-2694)

METHOD

VOLTAGE DECAY

Detailed analysis of the method and a description of the equipment necessary to carry it out are given.

55M1 Malkovska, M.
*DIFFUSION DISTANCES OF ELECTRONS AND HOLES IN GERMANIUM, MEASURED BY X-RAYS (In Russian)
Czech. J. Phys., vol. 5, pp. 545-546, December 1955. (PA:56-8783)

METHOD

TRAVELLING SPOT

X-RAY SOURCE

55P1 Pell, E. M.
REVERSE CURRENT AND CARRIER LIFETIME AS A FUNCTION OF TEMPERATURE IN GERMANIUM JUNCTION DIODES
J. Appl. Phys., vol. 26, pp. 658-665, June 1955. (PA:55-7055)

EXPERIMENTAL

REVERSE CURRENT DECAY

LOW TEMPERATURE

S-R-H, MULTIPLE LEVELS

Details of the system used to control the temperature are included in this early paper on this method.

55S1 Schultz, B. H.
ANALYSIS OF THE DECAY OF PHOTOCONDUCTANCE IN GERMANIUM
Philips Res. Rep., vol. 10, pp. 337-348, October 1955. (PA:56-1246)

ANALYSIS

PC(M)

PHASE SHIFT, COMPARATOR

SURFACE

The influence of the condition of the surface on photoconductivity is analyzed. (See also 61B1.)

55S2 Spitzer, W. G., T. E. Firle, M. Cutler, R. G. Shulman, and M. Becker
MEASUREMENT OF THE LIFETIME ON MINORITY CARRIERS IN GERMANIUM
J. Appl. Phys., vol. 26, pp. 414-417, April 1955. (PA:55-5408)

METHOD

SPREADING RESISTANCE, PULSE DELAY

The pulse delay method is a modification of the drift field method (55H1); the transient spreading resistance method is first described (see also 57I1). Both methods give a value for lifetime in a localized region of the sample.

55S3 Stevenson, D. T., and R. J. Keyes
MEASUREMENT OF CARRIER LIFETIMES IN GERMANIUM AND SILICON
J. Appl. Phys., vol. 26, pp. 190-195, February 1955. (PA:55-2745)

METHOD

PCD

SURFACE

This early paper on the method contains a discussion of the necessary apparatus and corrections for surface recombination in rectangular and cylindrical specimens.

55V1 Van Roosbroeck, W.
INJECTED CURRENT CARRIER TRANSPORT IN A SEMI-INFINITE SEMICONDUCTOR AND THE DETERMINATION OF LIFETIMES AND SURFACE RECOMBINATION VELOCITIES
J. Appl. Phys., vol. 26, pp. 380-391, April 1955. (PA:55-5405)

ANALYSIS

General solutions and particular solutions for a wide variety of interesting conditions are given.

1956

56A1 Adirovich, E. I., and G. M. Guro
CHARACTERISTIC TIMES OF ELECTRONIC PROCESSES IN SEMICONDUCTORS
Soviet Phys. Dokl., vol. 1, pp. 306-309, January 1957. (PA:57-364)

ANALYSIS

PULSE DECAY, TRAVELLING SPOT

S-R-H

After developing appropriate equations for decay time in the presence of S-R-H centers, the authors show that the decay time determined by either of these methods does not always correspond with the minority carrier lifetime in the presence of large concentrations of S-R-H centers.

56A2 Armstrong, H. L.
ON OPEN CIRCUIT TRANSIENT EFFECTS IN
POINT CONTACT RECTIFIERS
J. Appl. Phys., vol. 27, pp. 420-421,
April 1956. (PA:57-387)

ANALYSIS

VOLTAGE DECAY

For small hemispherical junctions, the transient decay is shown to depend on the junction radius rather than the lifetime. In the limit of large radius the decay is similar to that in planar p-n junctions. (See 56G1.)

56D1 deVore, H. G.
SPECTRAL DISTRIBUTION OF PHOTOCONDUCTIVITY
Phys. Rev., vol. 102, pp. 86-91,
April 1, 1956. (PA:56-3743)

ANALYSIS

PC

SPECTRAL RESPONSE

SURFACE

The peak which occurs in photoconductivity spectra near the band edge is attributed to surface recombination effects. The analysis is extended in 59B2.

56E1 Evans, D. M.
MEASUREMENTS ON ALLOY-TYPE GERMANIUM TRANSISTORS AND THEIR RELATION TO THEORY
J. Electronics, vol. 1, pp. 461-476,
March 1956. (EA:56-4082)

EXPERIMENTAL

BASE TRANSPORT

BRIDGE

Frequency variation of the base transport factor is used to obtain an effective lifetime. To determine the base transport factor at low frequency a bridge method, more fully described in 58H1, is used and at high frequency the emitter-base impedance is used. The technique was subsequently extended to silicon transistors by the author.

56G1 Garreta, O., and J. Grosvalet
PHOTO-MAGNETO-ELECTRIC EFFECT IN SEMICONDUCTORS
Prog. in Semiconductors, vol. 1,
John Wiley & Sons, Inc., New York,
pp. 166-194, 1956.

REVIEW

PME, PME(M), PME(T)

PHASE SHIFT, RATIO

Most aspects of the PME effect are discussed in a thorough manner, but the effect of trapping is not considered.

56G2 Glinchuk, K. D., E. G. Miseliuk, and E. I. Rashba
MEASUREMENT OF RATE OF RECOMBINATION OF CARRIERS BY CONDUCTIVITY MODULATION
Soviet Phys. Tech. Phys., vol. 1,
pp. 2521-2528, December 1956.
(PA:57-7097)

METHOD

PC, TRAVELLING SPOT

The methods are compared and differences in "lifetime" in the presence of trapping are noted. Effects of surface recombination and sweep-out are observed.

56H1 Harrick, N. J.
LIFETIME MEASUREMENTS OF EXCESS CARRIERS IN SEMICONDUCTORS
J. Appl. Phys., vol. 27, pp. 1439-1442, December 1956. (PA:57-3255)

METHOD

PC-IR

CONTACTLESS

This contactless method involves the determination of the density of the optically injected excess carriers as a function of distance from the surface where they are generated by means of infrared absorption. Trapping effects are neglected; low surface recombination velocity is required.

56H2 Henisch, H. K., and J. Zucker
CONTACTLESS METHOD FOR THE ESTIMATION OF RESISTIVITY AND LIFETIME OF SEMICONDUCTORS
Rev. Sci. Instrum., vol. 27, pp. 409-410, June 1956. (CA:57-51-12639c)

METHOD

PC-Q

CONTACTLESS

A rapid method which must be calibrated against some other method is described briefly.

56H3 Hogarth, C. A.
ON THE MEASUREMENT OF MINORITY CARRIER LIFETIMES IN SILICON
Proc. Phys. Soc., vol. B69, pp. 791-795, August 1956. (PA:57-1295)

ANALYSIS

PCD, TRAVELLING SPOT, DRIFT FIELD

SURFACE TREATMENT (n-Si, p-Si)

TRAPPING

Three methods are discussed from the point of view of influence of traps. With low surface recombination velocity, the travelling spot method is shown to yield satisfactory results. A short light pulse is recommended for use with the PCD method to reduce the influence of trapping.

56H4 Heywang, W., and M. Zerbst
ON THE DETERMINATION OF VOLUME AND
SURFACE RECOMBINATION EFFECTS FOR
CHARGE CARRIERS IN SEMICONDUCTORS
(In German)
Z. Naturforsch., vol. 11a, pp. 256-
257, March 1956. (PA:56-5863)

METHOD
PCD
SURFACE

The influence of surface recombination
on the shape of the PCD curve is discussed
for cylindrical silicon rods.

56K1 Kurnick, S. W., and R. N. Zitter
PHOTOCONDUCTIVE AND PHOTOELECTRO-
MAGNETIC EFFECTS IN InSb
J. Appl. Phys., vol. 27, pp. 278-285,
March 1956. (PA:56-2891)

EXPERIMENTAL
PC, PME
RATIO

<0.1

SURFACE TREATMENT (p-InSb), SPECIMEN SHAPING,
LOW TEMPERATURE

Trapping effects at 77 K were neglec-
ted in this paper; see 58Z1.

56K2 Kalashnikov, S. G.
RECOMBINATION OF ELECTRONS AND HOLES
WHEN VARIOUS TYPES OF TRAPS ARE
PRESENT
Soviet Phys. Tech. Phys., vol. 1.,
pp. 237-247, February 1956.
(PA:56-8776)

MODEL
MULTIPLE LEVELS

This is an early paper which considers
the role of interacting levels; cases when
the lifetime is influenced significantly
are discussed.

56L1 Landsburg, P. T.
DEFECTS WITH SEVERAL TRAPPING LEVELS
IN SEMICONDUCTORS
Proc. Phys. Soc., vol. B69, pp. 1056-
1059, October 1956. (PA:57-3263)

MODEL
MULTIPLE LEVELS

This is one of the earliest papers to
point out that multiple levels may not be
independent of each other.

56S1 Sorokin, O. V.
MEASUREMENT OF THE LIFETIME, DIFFUSION
COEFFICIENT, AND RATE OF SURFACE RE-
COMBINATION FOR NONEQUILIBRIUM CURRENT
CARRIERS IN A THIN SEMICONDUCTOR
SPECIMEN
Soviet Phys. Tech. Phys., vol. 1.,
pp. 2390-2396, November 1956.
(PA:57-7908)

ANALYSIS
FLYING SPOT

A modification of the method which
employs two point probes is described in
detail. The necessary apparatus is indi-
cated.

56V1 Van Roosbroeck, W.
THEORY OF THE PHOTOMAGNETOELECTRIC
EFFECT IN SEMICONDUCTORS
Phys. Rev., vol. 101, pp. 1714-1725,
March 15, 1956. (PA:56-3720)

ANALYSIS
PME

An error in previously assumed bound-
ary conditions (53M1) is pointed out and
correct, general equations are obtained
with fewer restrictive assumptions than
heretofore.

56W1 Wertheim, G. K., and W. M. Augustyniak
MEASUREMENT OF SHORT CARRIER LIFETIMES
Rev. Sci. Instrum., vol. 27, pp. 1062-
1064, December 1956. (PA:57-4331)

METHOD
BOMBARDMENT DECAY
ELECTRON INJECTION
0.01-10

Details of the modifications required
for a commercial accelerator are discussed
and the effects of radiation damage under
operating conditions are shown to be
negligible.

56W2 Watters, R. L., and G. W. Ludwig
MEASUREMENT OF MINORITY CARRIER
LIFETIME IN SILICON
J. Appl. Phys., vol. 27, pp. 489-497,
May 1956. (PA:56-4402)

METHOD
PCD, DRIFT FIELD
OHMIC CONTACTS (n-Si, p-Si), LIGHT SOURCE

A detailed study of the PCD method
as applied to silicon is presented, and many
of its limitations are discussed. The drift
field method is described briefly but is not
used for precise measurements.

- 57A1 Armstrong, H. L.
COMPARATOR METHOD FOR OPTICAL LIFE-
TIME MEASUREMENTS ON SEMICONDUCTORS
Rev. Sci. Instrum., vol. 28, p. 202,
March 1957. (CA:57-51-12640d)

METHOD

PCD

COMPARATOR

A direct reading technique for PCD
measurements is described briefly.

- 57B1 Buck, T. M., and F. S. McKim
MEASUREMENTS ON THE PME EFFECT IN
GERMANIUM
Phys. Rev., vol. 106, pp. 904-909,
June 1, 1957. (PA:57-7103)

EXPERIMENTAL

PC, PME

RATIO

Lifetime measured by PME-PC ratio
method is shown to be equivalent to that
measured by PCD. This result is not ex-
pected to be valid in the presence of
trapping, but trapping is not considered
in the paper.

- 57B2 Byczkowski, M., and J. R. Madigan
MINORITY CARRIER LIFETIME IN p-n
JUNCTION DEVICES
J. Appl. Phys., vol. 28, pp. 878-881,
August 1957. (PA:58-4011)

ANALYSIS

REVERSE RECOVERY

Expressions relating reverse recovery
time and carrier lifetime are developed for
arbitrary base widths. If the base width
is at least three times the diffusion length
the long-base expression for lifetime is
shown to be valid. (See 54K1.) A closed
form for the general expression has been
developed subsequently (66D1).

- 57C1 Clarke, D. H.
SEMICONDUCTOR LIFETIME AS A FUNCTION
OF RECOMBINATION STATE DENSITY
J. Electronics Control, vol. 3,
pp. 375-386, October 1957.
(PA:58-4965)

ANALYSIS

PCD, PC

S-R-H

Analysis of S-R-H model is extended
to include transient behavior. Both high
and low densities of recombination centers
are considered. Lifetimes associated with
steady-state and transient photoconductivi-
ty are compared. (See also 57G2.)

- 57D1 Dale, E. B., R. W. Beck, C. S. Peet,
and A. C. Beer
MEASUREMENTS OF BULK LIFETIME IN
SILICON (Scientific Report No. 2,
Contract AF19(604)-1852)
AFCRC Report-TN-57-370, May 15, 1957
AD-117 072

METHOD

PCD, SPREADING RESISTANCE, PHOTOINJECTION-
SWEEP OUT, PULSE DELAY

This preliminary study concludes that
the PCD method is superior to the others
for evaluation measurements.

- 57E1 Ellis, S. G.
SURFACE STUDIES ON SINGLE-CRYSTAL
GERMANIUM

J. Appl. Phys., vol. 28, pp. 1262-
1269, November 1957. (PA:58-9148)

PROCEDURE

SURFACE TREATMENT (n-Ge)

Procedures for controlling surface
recombination of n-type germanium are
included in this initial survey.

- 57E2 Engler, A. R., and C. J. Kevane
DIRECT READING MINORITY CARRIER LIFE-
TIME MEASURING APPARATUS
Rev. Sci. Instrum., vol. 28, pp. 548-
551, July 1957. (PA:58-3101)

METHOD

PC(M)

PHASE SHIFT, COMPARATOR

A comparator apparatus for measuring
photoconductivity is described. A compli-
cated nomogram for making corrections for
surface recombination (fundamental mode
only) in long, rectangular filaments is
included.

- 57G1 Goodwin, D. W.
PHOTO EFFECTS IN INDIUM ANTIMONIDE
Report of the Meeting on Semiconduc-
tors, The Physical Society, London,
1957, pp. 137-145. (PA:57-7902)

METHOD

PC, PME

SPECTRAL RESPONSE

Spectral dependence of PME and PC is
used to obtain carrier lifetime; trapping
effects are not considered.

57G2 Goureau (Guro), G. M.
DECAY LAW FOR THE CONCENTRATION OF
NONEQUILIBRIUM CHARGE CARRIERS IN
SEMICONDUCTORS
Soviet Phys. JETP, vol. 6, pp. 123-
129, January 1958. (PA:58-3098)

MODEL
S-R-H

Decay laws for a variety of circum-
stances are derived. In many cases the
decay is not exponential. (See also 57C1.)

57G3 Garbuny, M., T. P. Vogel, and J. R.
Hansen
METHOD FOR THE GENERATION OF VERY
FAST LIGHT PULSES
Rev. Sci. Instrum., vol. 28, pp. 826-
827, October 1957. (PA:58-5830)

PROCEDURE

PCD

>0.01

LIGHT SOURCE

A multiple reflection system consis-
ting of rotating and stationary mirrors is
described. Light pulses as short as 40 ns
were obtained.

57H1 Henderson, J. C., and J. R. Tillman
MINORITY CARRIER STORAGE IN SEMI-
CONDUCTOR DIODES
Proc. IEE, Paper 2293R, vol. 104B,
pp. 318-332, January 1957.
(PA:57-2192)

ANALYSIS

VOLTAGE DECAY, REVERSE RECOVERY, REVERSE
CURRENT DECAY

The relationship between recovery time
and lifetime for a wide variety of condi-
tions for both plane (p-n junction) and
hemispherical (point-contact) diodes is
discussed from a device viewpoint.

57I1 Iglitsyn, M. I., Yu. A. Kontsevoi,
V. D. Kudin, and A. A. Meier
MEASURING THE LIFETIME OF CHARGE
CARRIERS IN SEMICONDUCTORS
Soviet Phys. Tech. Phys., vol. 2,
pp. 1306-1315, July 1957.
(PA:58-7921)

ANALYSIS

SPREADING RESISTANCE

The method, first described in 55S2,
is analyzed in greater detail and conditions
for its correct use are given. The authors
recommend the method strongly in preference
to the travelling spot, drift field, PCD,
and pulse decay methods.

57I2 Iglitsyn, M. I., Yu. A. Kontsevoi,
and V. D. Kudin
MEASUREMENT OF LIFETIME IN SILICON
MONOCRYSTALS
Soviet Phys. Tech. Phys., vol. 2,
pp. 1316-1321, July 1957.
(PA:58-7922)

EXPERIMENTAL

SPREADING RESISTANCE

OHMIC CONTACTS (n-Si, p-Si), INJECTING
CONTACTS (n-Si, p-Si)

The method discussed in 57I1 is
extended to silicon with good results. The
effects of trapping are generally found to
be small.

57J1 Johnson, E. O.
MEASUREMENT OF MINORITY CARRIER LIFE-
TIMES WITH THE SURFACE PHOTOVOLTAGE
J. Appl. Phys., vol. 28, pp. 1349-
1353, November 1957. (PA:58-8760)

METHOD

SPV DECAY

CONTACTLESS

SURFACE TREATMENT

This method appears to be more
sensitive to trapping effects than the PCD
method. Steady-state surface photovoltage
methods described elsewhere (see 61G1,
64B3) are better.

57L1 Landsberg, P. T.
A CONTRIBUTION TO THE RECOMBINATION
STATISTICS OF EXCESS CARRIERS IN
SEMICONDUCTORS
Proc. Phys. Soc., vol. B70, pp. 282-
296, March 1957. (PA:57-4330)

MODEL

MULTIPLE LEVELS, BAND-TO-BAND RECOMBINATION
Effects of degeneracy and large excess
carrier density are considered in this
theoretical treatment.

57P1 Penin, N. A., and K. V. Yakunina
DEPENDENCE OF CAPACITANCE AND RESIST-
ANCE OF GERMANIUM DIODES ON FREQUENCY
AND POSITIVE BIAS CURRENT
Radio Engng. Electronic Phys., vol. 2,
pp. 154-166, September 1957.
(EA:59-996)

EXPERIMENTAL

DIFFUSION CAPACITANCE

Extraction of lifetime from junction
capacitance measurements is discussed in
some detail.

57R1 Ross, B., and J. R. Madigan
THERMAL GENERATION OF RECOMBINATION
CENTERS IN SILICON
Phys. Rev., vol. 108, pp. 1428-1433,
December 15, 1957. (PA:58-6998)

EXPERIMENTAL

REVERSE RECOVERY

LOW TEMPERATURE, HIGH TEMPERATURE

S-R-H

Details of the technique as applied to
silicon are given together with a typical
S-R-H analysis.

57R2 Rose, A.
LIFETIMES OF ELECTRONS AND HOLES IN
SOLIDS
Prog. in Semiconductors, vol. 2,
John Wiley & Sons, Inc., New York,
1957, pp. 109-136.

REVIEW

S-R-H, MULTIPLE LEVELS, TRAPPING

Characteristics of various types of
recombination centers are considered from
a general viewpoint.

57S1 Sandiford, D. J.
CARRIER LIFETIME IN SEMICONDUCTORS
FOR TRANSIENT CONDITIONS
Phys. Rev., vol. 105, p. 524,
January 15, 1957. (PA:57-4327)

ANALYSIS

PCD

S-R-H

Differences between various "life-
times" when a large concentration of
trapping centers is present are pointed
out emphatically.

57S2 Sah, C. T., R. N. Noyce, and
W. Shockley
CARRIER GENERATION AND RECOMBINATION
IN p-n JUNCTIONS AND p-n JUNCTION
CHARACTERISTICS
Proc. IRE, vol. 45, pp. 1228-1243,
September 1957. (PA:58-178)

MODEL

S-R-H

This basic paper on generation-
recombination current in p-n junctions is
one of the classics of the semiconductor
literature.

57S3 Smirnov, L. S.
MEASUREMENT OF SHORT LIFETIMES OF
CHARGE CARRIERS IN GERMANIUM
Soviet Phys. Tech. Phys., vol. 2,
pp. 2299-2301, November 1957.
(PA:58-1060)

EXPERIMENTAL

JUNCTION PHOTOCURRENT

0.01-2

A large area p-n junction is employed
in a technique suitable only for determina-
tion of short lifetimes.

57S4 Sorokin, O. V.
A METHOD FOR MEASURING THE VOLUME
LIFETIME AND THE DIFFUSION COEFFICIENT
OF CURRENT CARRIERS BY MEASURING THE
RESISTANCE OF A SEMICONDUCTOR IN A
MAGNETIC FIELD
Soviet Phys. Tech. Phys., vol. 2,
pp. 2572-2574, December 1957.
(PA:58-4000)

METHOD

SUHL EFFECT

Measurements on two specimens of dif-
ferent size are required for this technique
which is suitable only for near-intrinsic
material. Its basis is similar to that in
53H1.

57V1 van der Pauw, L. J.
ANALYSIS OF PHOTOCONDUCTANCE IN
SILICON
Philips Res. Rep., vol. 12, pp. 364-
376, August 1957. (PA:59-317)

ANALYSIS

PC(M)

PHASE SHIFT

An analysis appropriate for thick
specimens and relatively low frequencies
is developed. (See also 61B1.)

57V2 van Heerden, P. J.
PRIMARY PHOTO CURRENT IN CADMIUM
SULFIDE
Phys. Rev., vol. 106, pp. 468-473,
May 1, 1957. (PA:57-5350)

ANALYSIS

CHARGE COLLECTION EFFICIENCY

Although this paper is concerned with
a different aspect, the discussion of the
charge collection curve is pertinent to
lifetime measurements. (See also 59D2,
66C3.)

- 58A1 Aigrain, P.
RECOMBINATION PROCESSES IN SEMICONDUCTORS

Nuovo Cimento Suppl., vol. 7,
pp. 724-729, 1958. (PA:59-299)

REVIEW

S-R-H, RADIATIVE RECOMBINATION

This concise, introductory review considers both surface and bulk recombination mechanisms.

- 58B1 Buck, T. M., and F. S. McKim
EFFECTS OF CERTAIN CHEMICAL TREATMENTS AND AMBIENT ATMOSPHERES ON SURFACE PROPERTIES OF SILICON

J. Electrochem. Soc., vol. 105,
pp. 709-714, December 1958.
(CA:59-53-2808c)

PROCEDURE

SURFACE TREATMENT (n-Si, p-Si)

Methods for reducing surface recombination at silicon surfaces are described.

- 58B2 Bath, H. M., and M. Cutler
MEASUREMENT OF SURFACE RECOMBINATION VELOCITY IN SILICON BY STEADY-STATE PHOTOCONDUCTANCE

J. Phys. Chem. Solids, vol. 5,
pp. 171-179, May 1958. (PA:59-8120)

METHOD

PC

Although primarily directed toward surface recombination measurements, this paper discusses a number of details of the method which are also appropriate for lifetime measurements. Significant variations in surface recombination velocity with excess carrier density are observed.

- 58B3 Blakemore, J. S.
LIFETIME IN p-TYPE SILICON
Phys. Rev., vol. 110, pp. 1301-1308,
June 15, 1968. (PA:58-4992)

EXPERIMENTAL

PCD

S-R-H, MULTIPLE LEVELS

Experiments on trap-free silicon show that the lifetime varies with electron density. Comments on filtering incident light are included; use of thick filters is advocated.

- 58B4 Bernard, M.
RECOMBINATION IN TRAPS WITH TWO LEVELS IN SEMICONDUCTORS (In French)
J. Electronics Control, vol. 5,
pp. 15-18, July 1958. (PA:58-6965)

MODEL

MULTIPLE LEVELS

This has less general treatment of the problem than 58S1, which appeared independently.

- 58B5 Bemski, G.
RECOMBINATION IN SEMICONDUCTORS
Proc. IRE, vol. 46, pp. 990-1004,
June 1958. (PA:58-4957)

REVIEW

PCD, PULSE DECAY, PME, TRAVELLING SPOT, FLYING SPOT, DRIFT FIELD

S-R-H, TRAPPING, RADIATIVE RECOMBINATION, SURFACE

This excellent, general review of early work covers mechanisms, models, and methods. A comprehensive bibliography (131 entries) which covers papers published through 1957 is included. Several methods besides those listed are mentioned briefly.

- 58B6 Brown, D. A. H.
MAJORITY CARRIER LIFETIME IN COPPER-DOPED GERMANIUM AT 20 K
J. Electronics Control, vol. 4,
pp. 341-349, April 1958. (PA:58-4974)

EXPERIMENTAL

PC, NOISE

LOW TEMPERATURE

The effects of background radiation on photoconductivity measurements at 20 K is noted. Agreement is obtained between the two methods but not with theory.

- 58B7 Braunstein, R., A. R. Moore, and F. Herman
INTRINSIC OPTICAL ABSORPTION IN GERMANIUM-SILICON ALLOYS
Phys. Rev., vol. 109, pp. 695-710,
February 1, 1958. (PA:58-8687)

PROCEDURE

ABSORPTION COEFFICIENT (Ge, Si)

Absorption coefficient data for pure silicon and germanium are included in this paper on alloys.

58B8 Beck, R. W., C. S. Peet, and
A. C. Beer
MEASUREMENT OF BULK LIFETIME IN
SILICON (Scientific Report No. 3,
Contract AF19(604)-1852)
AFCRC Report-TN-59-110, December 15,
1958. AD-208 773

METHOD

PCD, PME

The PME effect was not found to give additional useful results in trap-free material. A discussion of the variation of lifetime with injection level and temperature is given.

58G1 Grover, N. B., and E. Harnik
SWEEP-OUT EFFECTS IN THE PHASE SHIFT
METHOD OF CARRIER LIFETIME MEASURE-
MENTS
Proc. Phys. Soc., vol. 72, pp. 267-
269, August 1958. (PA:58-7920)

ANALYSIS

PC(M)

PHASE SHIFT

Correction factors for the effect of carrier sweep-out are given for cases of illumination (1) of an entire face and (2) of a narrow band on the surface.

58G2 Gremmelmaier, R.
IRRADIATION OF p-n JUNCTIONS WITH
GAMMA RAYS: A METHOD FOR MEASURING
DIFFUSION LENGTH
Proc. IRE, vol. 46, pp. 1045-1049,
June 1958. (PA:58-4996)

METHOD

JUNCTION PHOTOCURRENT

GAMMA SOURCE

Details of the method and the procedure for determining the carrier generation rate are given.

58H1 Hyde, F. J.
SOME MEASUREMENTS ON COMMERCIAL TRAN-
SISTORS AND THEIR RELATION TO THEORY
Proc. IEE, vol. 105B, pp. 45-52,
January 1958. (EA:58-858)

EXPERIMENTAL

VOLTAGE DECAY, BASE TRANSPORT
BRIDGE

The bridge method for measuring common emitter current gain (see 56E1) is described in some detail, effects of reduced emitter efficiency and of surface recombination are considered, the possibility of trapping is raised, and the effective lifetime deduced from bridge measurements is compared with the voltage decay characteristic of the emitter-base diode with floating collector.

58H2 Harnik, E., A. Many, and N. B. Grover
PHASE SHIFT METHOD OF CARRIER LIFE-
TIME MEASUREMENTS IN SEMICONDUCTORS
Rev. Sci. Instrum., vol. 29, pp. 889-
891, October 1958. (PA:59-3446)

METHOD

PC(M)

PHASE SHIFT, COMPARATOR

LIGHT SOURCE

A direct reading technique suitable for lifetimes greater than a few micro-seconds is described. Details of a Kerr cell shutter are given.

58H3 Hill, J. E., and K. M. van Vliet
GENERATION-RECOMBINATION NOISE IN
INTRINSIC AND NEAR-INTRINSIC GERMANIUM
CRYSTALS

J. Appl. Phys., vol. 29, pp. 177-182,
February 1958. (PA:58-8767)

EXPERIMENTAL

NOISE

The relationship between g-r noise and lifetime is discussed and used to interpret noise measurements on several germanium crystals at room temperature and above.

58K1 Kalashnikov, S. G., and E. G.
Landsberg
INVESTIGATION OF THE PHOTOMAGNETO-
ELECTRIC EFFECT AS A MEANS OF
DETERMINING THE BULK DIFFUSION LENGTH
IN GERMANIUM
Soviet Phys. Tech. Phys., vol. 3,
pp. 1288-1294, July 1958.
(PA:59-3470)

METHOD

PC, PME

RATIO

Various problems of experimental procedure are studied to determine their effect on the method. Since trapping was not a problem in the specimens studied, the results agreed with measurements made by the travelling spot method.

58L1 Lashkarev, V. E., E. I. Rashba,
V. A. Romanov, and E. A. Demidenko
THE KINETICS OF CERTAIN ELECTRON
PROCESSES IN SEMICONDUCTORS
Soviet Phys. Tech. Phys., vol. 3,
pp. 1707-1722, September 1958.
(PA:59-3448)

ANALYSIS

PC(M), PME(M), BULK PV(M)

PHASE SHIFT

TRAPPING, SURFACE

A detailed analysis of recombination statistics is carried out for a variety of conditions.

58M1 McKelvey, J. P.
VOLUME AND SURFACE RECOMBINATION OF
INJECTED CARRIERS IN CYLINDRICAL
SEMICONDUCTOR INGOTS
IRE Trans. Electron Devices, vol.
ED-5, pp. 260-264, October 1958.
(PA:59-5683)

ANALYSIS

PCD

SURFACE

The effect of surface recombination on the measured lifetime of carriers in a right circular cylinder with contacts (infinite surface recombination) on the ends and uniform initial distribution of excess carriers is calculated; the influence of higher modes of decay is noted.

58M2 Many, A., and R. Bray
LIFETIME OF EXCESS CARRIERS IN
SEMICONDUCTORS
Prog. in Semiconductors, vol. 3,
John Wiley & Sons, Inc., New York,
1958, pp. 117-151.

REVIEW

S-R-H, TRAPPING

The emphasis here is on mechanisms of recombination rather than on determination of lifetime.

58N1 Nomura, K. C., and J. S. Blakemore
DECAY OF EXCESS CARRIERS IN
SEMICONDUCTORS
Phys. Rev., vol. 112, pp. 1607-1615,
December 1, 1958. (PA:59-2320)

ANALYSIS

PCD

S-R-H

This general analysis extends the S-R-H equations to the transient case with arbitrary recombination center density. The case where the Fermi level lies in the same half of the gap as the energy level of the center is discussed in detail. The opposite case is discussed in 61N1.

58R1 Ridley, B. K.
MEASUREMENT OF LIFETIME BY THE
PHOTOCONDUCTIVE DECAY METHOD
J. Electronics Control, vol. 5, pp.
549-558, December 1958. (PA:59-1441)

ANALYSIS

PCD

SURFACE

The influence of surface recombination on the decay curve is considered in detail. Nonuniform generation is not considered but the merits of pulsed and steady sources are compared. See also 58S3, which considers the same problem from a different viewpoint. Errors in Eqs. 13 and 17 are corrected in J. Electronics Control, vol. 15, p. 492, November 1963.

58S1 Sah, C. T., and W. Shockley
ELECTRON-HOLE RECOMBINATION STATISTICS
IN SEMICONDUCTORS THROUGH FLAWS WITH
MANY CHARGE CONDITIONS
Phys. Rev., vol. 109, pp. 1103-1115,
February 15, 1958. (PA:58-1678)

MODEL

MULTIPLE LEVELS

Non-equilibrium statistics are developed for a multiple-charge-condition recombination center. The treatment is similar in form to that for the single-level centers (S-R-H).

58S2 Sandiford, D. J.
TEMPERATURE DEPENDENCE OF CARRIER
LIFETIME IN SILICON
Proc. Phys. Soc., vol. 71, pp. 1002-
1006, June 1958. (PA:58-4010)

EXPERIMENTAL

PCD

S-R-H

Pertinent comments regarding the effects of filtering, trapping, and injection level are included in this paper.

58S3 Sim, A. C.
A NOTE ON SURFACE RECOMBINATION VELOCITY AND PHOTOCONDUCTIVE DECAYS
J. Electronics Control, vol. 5,
pp. 251-255, September 1958.
(PA:59-3447)

ANALYSIS

PCD

SURFACE

The effects of surface recombination are shown to be greater than ordinarily assumed, especially in the early stages of decay. Correction factors are given.

58V1 van Roosbroeck, W., and T. M. Buck
METHODS FOR DETERMINING VOLUME LIFE-
TIMES AND SURFACE RECOMBINATION
VELOCITIES

Transistor Technology, vol. 3,
F. J. Biondi, Ed., D. Van Nostrand,
Princeton, N. J., 1958, chapter 9,
pp. 309-324.

REVIEW

PCD, PULSE DECAY, PME, TRAVELLING SPOT,
DRIFT FIELD, REVERSE RECOVERY

A variety of transient and steady-
state methods and their interpretation in
the absence of trapping is discussed. An
annotated bibliography is included.
Recommended.

58W1 Wertheim, G. K.
TRANSIENT RECOMBINATION OF EXCESS
CARRIERS IN SEMICONDUCTORS
Phys. Rev., vol. 109, pp. 1086-1091,
February 15, 1958. (PA:58-7924)

MODEL

S-R-H, MULTIPLE LEVELS

Time constants for decay of injected
carrier density are developed for several
cases.

58Z1 Zitter, R. N.
ROLE OF TRAPS IN THE PHOTOELECTRO-
MAGNETIC AND PHOTOCONDUCTIVE EFFECTS
Phys. Rev., vol. 112, pp. 852-855,
November 1, 1958. (PA:59-4602)

ANALYSIS

PC, PME

RATIO

TRAPPING

This phenomenological treatment
clearly shows the differences to be expected
when trapping occurs.

1959

59A1 Amith, A.
PHOTOCONDUCTIVE AND PHOTOELECTRO-
MAGNETIC LIFETIME DETERMINATION IN THE
PRESENCE OF TRAPPING. I. SMALL
SIGNALS

Phys. Rev., vol. 116, pp. 793-802,
November 15, 1959. (PA:60-2865)

ANALYSIS

PC, PME

RATIO

TRAPPING

The author shows that the ratio method
for determining lifetime from PME and PC
measurements is unreliable if trapping is
present.

59A2 Adirovich, E. I.
CONDUCTANCE AND THE VOLTAGE TRANS-
MISSION COEFFICIENT OF A SEMICONDUCTOR
DIODE IN THE TRANSIENT STATE

Soviet Phys. Solid State, vol. 1, pp.
1019-1028, January 1960. (PA:60-4329)

METHOD

DIFFUSION CAPACITANCE

PHASE SHIFT

A method for measuring short lifetimes
at frequencies less than the reciprocal of
the lifetime is proposed. (See also 62A1.)

59B1 Beattie, A. R., and P. T. Landsberg
AUGER EFFECT IN SEMICONDUCTORS
Proc. Phys. Soc., vol. 249A, pp. 16-
29, January 1, 1959. (PA:60-2869)

MODEL

AUGER EFFECT

The analysis of the effect is more com-
plete than earlier ones. Comparisons with
experimental results on InSb below room temp-
erature are included.

59B2 Bir, L. G.
THE EFFECT OF SURFACE RECOMBINATION
ON THE PHOTOCONDUCTIVITY OF SEMI-
CONDUCTORS

Soviet Phys. Solid State, vol. 1,
pp. 62-69, June 1959. (PA:60-617)

ANALYSIS

PC

SPECTRAL RESPONSE

SURFACE

The work of deVore (56D1) is extended
to include the case of thick space charge
layers at the surface.

59B3 Barsukov, Yu. K.
TRANSIENT BLOCKING PROCESSES IN PLANAR
SEMICONDUCTOR DIODES FOR HIGH CURRENTS
Soviet Phys. Solid State, vol. 1,
p. 544, October 1959. (EA:59-7395)

EXPERIMENTAL

REVERSE RECOVERY

Experiments which support the conclu-
sion of 65M3 that high injection does not
appreciably alter the recovery time-lifetime
relationship are described.

59D1 Das, M. B., and A. R. Boothroyd
ON THE DETERMINATION OF THE MINORITY
CARRIER LIFETIME IN THE BASE REGION
OF TRANSISTORS
J. Electronics Control, vol. 7,
pp. 534-539, December 1959.
(PA:60-15980)

METHOD
BASE TRANSPORT

This method, although it requires measurements of a number of small-signal transistor parameters, avoids the influence of emitter efficiency on the beta cut-off frequency which is frequently used to determine effective lifetime in the base region of a transistor.

59D2 Davis, W. D.
LIFETIMES AND CAPTURE CROSS SECTIONS
IN GOLD-DOPED SILICON
Phys. Rev., vol. 114, pp. 1006-1008,
May 15, 1959. (PA:59-8784)

EXPERIMENTAL
CHARGE COLLECTION EFFICIENCY
ALPHA SOURCE
SURFACE TREATMENT (n-Si, p-Si)

Some details of the method are given together with the results. A more complete description may be found in 66C3. (See also 57V2.)

59G1 Gosar, P.
ON THE MEASUREMENT OF THE MINORITY
CARRIER LIFETIME BY THE SURFACE PHOTO-
VOLTAGE EFFECT (In French)
CR Acad. Sci., vol. 248, pp. 3139-
3141, June 1, 1959. (PA:59-11031)

ANALYSIS
SPV DECAY

Basic equations for the transient decay of surface photovoltage are developed. The dependence of the decay time on wavelength of incident light is discussed.

59H1 Hilsum, C.
PROPERTIES OF p-TYPE INDIUM ANTIMONIDE.
II. PHOTOELECTRIC PROPERTIES AND
CARRIER LIFETIME
Proc. Phys. Soc., vol. 74, pp. 81-86,
July 1, 1959. (PA:60-4370)

EXPERIMENTAL
PC, PME
RATIO
PHOTON FLUX CALIBRATION

The experimental arrangement used in these measurements is described in some detail.

59H2 Huldt, L.
OPTICAL METHOD FOR DETERMINING CARRIER
LIFETIMES IN SEMICONDUCTORS
Phys. Rev. Letters, vol. 2, pp. 3-5,
January 1, 1959. (PA:59-4574)

ANALYSIS
PC(M)-IR

A method based on the dependence of the absorption on the frequency of interruption of the generating illumination is described. The possibility of measuring the electron and hole lifetimes independently is mentioned but not explained. (See 64N1.)

59H3 Harten, H. U.
SURFACE RECOMBINATION OF SILICON
Philips Res. Rep., vol. 14, pp. 346-
360, October 1959. (PA:60-2886)

PROCEDURE
SURFACE TREATMENT (n-Si, p-Si)
SURFACE

The effect of various ambients on surface recombination velocity are investigated. The results are very similar to those reported in 58B1. (See also 62H2.)

59K1 Kopylovskii, B. D.
THE PHASE METHOD OF MEASURING THE LIFE-
TIME AND SURFACE RECOMBINATION VELOC-
ITY OF NONEQUILIBRIUM CHARGE CARRIERS
IN SEMICONDUCTORS
Instrum. Exper. Tech., vol. 2, pp. 256-
260, March-April 1959. (EA:59-6406)

METHOD
PC(M)
PHASE SHIFT
>0.01

A brief description of an apparatus used successfully down to 5 μ s is given. Extension to 10 ns is projected.

59K2 Keller, W.
HIGH FREQUENCY MEASUREMENT OF THE VOL-
UME LIFETIME IN SILICON SINGLE CRYSTALS
(In German)
Z. Angew. Phys., vol. 11, pp. 351-352,
September 1959. (PA:59-13310)

METHOD
PCD-Q
CONTACTLESS

Measurements are made on samples wrapped in plastic film so that contamination is avoided. (See also 65E2, 61W1.) The method is suitable for high resistivity silicon rods. (See also 62N1.)

59M1 Mironov, A. G.
ON THE THEORY OF PHOTOCONDUCTIVITY
AND PHOTOELECTROMAGNETIC EFFECT WHEN
TRAPPING LEVELS ARE PRESENT
Soviet Phys. Solid State, vol. 1,
pp. 471-473, October 1959.
(PA:60-1680)

ANALYSIS
PCD, PME(T)
RATIO
TRAPPING

The effect of trapping on the ratio
lifetime as calculated from the transient
PME effect and PCD is determined.

59M2 Moizhes, B. Ya.
ELIMINATION OF EDGE EFFECT DURING THE
MEASUREMENT OF THE PHOTOMAGNETIC EMF
IN SEMICONDUCTORS
Soviet Phys. Solid State, vol. 1,
pp. 1135-1138, February 1960.
(PA:60-6132)

ANALYSIS
PC, PME

Conditions under which the one dimen-
sional formulas usually used to calculate
the PME voltages are valid are developed
for the case when only part of the specimen
surface is illuminated. (See 60L2.)

5901 Okada, J.
EFFECT OF EXTERNAL ILLUMINATION ON
CARRIER LIFETIME IN SEMICONDUCTORS
J. Phys. Soc. Japan, vol. 14, pp.
1550-1557, November 1959.
(PA:60-20882)

ANALYSIS
PCD
MULTIPLE LEVELS, TRAPPING

The effect of external illumination
on the decay time is analyzed and the re-
sults are compared with solutions of the
steady state problem.

59R1 Ramsa, A. P., H. Jacobs, and F. A.
Brand
MICROWAVE TECHNIQUES IN MEASUREMENT
OF LIFETIME IN GERMANIUM
J. Appl. Phys., vol. 30, pp. 1054-
1060, July 1959. (PA:59-8111)

METHOD
PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICRO-
WAVE
CONTACTLESS
SPECIMEN SHAPING

This early paper describes the appa-
ratus required for these measurements and con-
siders some of the problems encountered with
both optical and probe injection. (See
60A1, 60J1, 61A1, 61J1, 63B1.)

59R2 Romanov, V. A.
A STUDY OF THE KINETICS OF PHOTO-
ELECTRIC PROCESSES IN SEMICONDUCTORS
Instrum. Exper. Tech., vol. 2,
pp. 929-934, November-December 1959.
(EA:61-5071)

METHOD
PC(M), PME(M)
PHASE SHIFT
LIGHT SOURCE
Details of the apparatus, including
a Kerr cell source, are given.

59S1 Sim, A. C.
A NOTE ON THE USE OF FILTERS IN PHOTO-
CONDUCTIVITY DECAY MEASUREMENTS
Proc. IEE, Paper 2885E, May 1959,
vol. 106B, Suppl. #15, pp. 308-310.
(PA:59-4573)

ANALYSIS
PCD
Relatively thick filters are recom-
mended when accurate lifetime measurements
are being made. Dependence of lifetime on
injection level is also discussed.

59W1 Walton, A. K., and T. S. Moss
THEORY OF ELECTRICAL AND PHOTOELECTRIC
EFFECTS FOR THREE CARRIERS IN A
MAGNETIC FIELD
Proc. Phys. Soc., vol. 73, pp. 399-
412, March 1959. (PA:59-7009)

ANALYSIS
PME
The effects of light and heavy holes
in the valence band of germanium are con-
sidered. Anisotropy of both conduction
and valence bands is neglected. Usually
the influence of the light hole on the
results is neglected; this paper suggests
that it should not be.

59W2 Waldner, M.
MEASUREMENT OF MINORITY CARRIER
DIFFUSION LENGTH AND LIFETIME BY
MEANS OF THE PHOTOVOLTAIC EFFECT
Proc. IRE, vol. 47, pp. 1004-1005,
May 1959. (PA:59-9606)

METHOD
JUNCTION PHOTOCURRENT
A simple scheme for carrying out the
measurements and some hazards in so doing
are described.

1960

- 60A1 Atwater, H. A.
MICROWAVE MEASUREMENT OF SEMICONDUCTOR
CARRIER LIFETIMES
J. Appl. Phys., vol. 31, pp. 938-939,
May 1960. (PA:60-9954)

ANALYSIS

PCD-MICROWAVE ABSORPTION, PULSE DECAY-
MICROWAVE

The conditions under which the decay
of the microwave attenuation has the same
time constant as the decay of the excess
carrier density are derived.

- 60B1 Blakemore, J. S., and K. C. Nomura
INFLUENCE OF TRANSVERSE MODES ON
PHOTOCONDUCTIVE DECAY IN FILAMENTS
J. Appl. Phys., vol. 31, pp. 753-
761, May 1960. (PA:60-7954)

ANALYSIS

PCD

SURFACE

A rather complete discussion of the
effects of nonuniform initial carrier dis-
tribution within the specimen on the shape
of the photoconductive decay curve is given.
Suggestions for masking the specimen and a
brief discussion of distortion which results
from a finite tail on the carrier generation
are also included.

- 60B2 Brand, F. A., A. N. Baker, and
H. L. Mette
SPECTRAL DISTRIBUTION OF THE PME
EFFECT IN Ge: EXPERIMENT
Phys. Rev., vol. 119, pp. 922-925,
August 1, 1960. (PA:60-13635)

EXPERIMENTAL

PC, PME

SPECTRAL RESPONSE, RATIO

SURFACE TREATMENT (n-Ge)

The influence of surface recombination
and depth of absorption on the PME signal
is discussed from an experimental viewpoint.

- 60B3 Bodó, Z.
DETERMINATION OF MINORITY CARRIER
LIFETIME IN SEMICONDUCTORS
*Solid State Phys. Electronics
Telecommunications*, Part 1, Academic
Press, New York, 1960, pp. 194-198.

METHOD

TRAVELLING SPOT

The photovoltage is measured as a
function of the radius of the incident light
spot rather than the more usual distance
between contact and spot. A surface with
zero recombination velocity is necessary for
accurate determination of carrier lifetime.

- 60B4 Bube, R. H.
PHOTOCONDUCTIVITY OF SOLIDS
John Wiley & Sons, Inc., New York,
1960

BOOK

PC

Although written with emphasis on
insulators rather than semiconductors, this
book offers valuable insights into the
phenomena of recombination and trapping.

- 60D1 de Kinder, W., and J. Vennik
MEASUREMENT OF MINORITY CARRIER LIFE-
TIME IN SEMICONDUCTORS (In French)
CR Acad. Sci., vol. 251, pp. 1275-1276,
September 26, 1960. (PA:61-2405)

METHOD

PCD-MICROWAVE ABSORPTION
CONTACTLESS

A modification of the apparatus
described in 59R1 permits the dependence
of reflectivity with conductivity to be
taken into account.

- 60D2 Dubrovskii, G. B., and V. K. Subashiev
DETERMINATION OF RECOMBINATION PARA-
METERS FROM THE SPECTRAL RESPONSE OF
A PHOTOCCELL WITH A p-n JUNCTION. II
Soviet Phys. Solid State, vol. 2,
pp. 1418-1425, January 1961.
(PA:60-15909)

EXPERIMENTAL

JUNCTION PHOTOCURRENT

SPECTRAL RESPONSE

ABSORPTION COEFFICIENT (Si)

Absorption coefficient data for pure
silicon over the wavelength range near the
band edge are included in this paper. (See
also 58B7.)

- 60G1 Goodwin, D. W.
PHOTOCONDUCTIVE EFFECTS IN INDIUM
ANTIMONIDE
*Solid State Phys. Electronics Tele-
communications*, Part 2, Academic Press,
New York, 1960, pp. 759-767.
(CA:61-55-9065b)

EXPERIMENTAL

PC, PME, NOISE

TRAPPING

Trapping is found to occur in p-InSb
from differences in lifetime as measured by
the PC and PME methods. In n-InSb no
trapping was observed and the PME, PC, and
noise power methods yielded similar values.

60G2 Grinberg, A. A., L. G. Paritzkii, and S. M. Ryvkin
THE EFFECT OF TRAPPING LEVELS IN SEMICONDUCTORS ON STEADY STATE PHOTO-CONDUCTIVITY AND NONEQUILIBRIUM CARRIER LIFETIME
Soviet Phys. Solid State, vol. 2, pp. 1403-1417, January 1961.
(PA:60-18060)

ANALYSIS

PC

TRAPPING

The effect of trapping is considered mathematically for a variety of circumstances.

60G3 Grinberg, A. A.
THE PHOTOMAGNETIC EFFECT IN ISOTROPIC SEMICONDUCTORS AND ITS USE IN MEASURING THE LIFETIME OF MINORITY CURRENT CARRIERS
Soviet Phys. Solid State, vol. 2, pp. 766-776, November 1960.
(PA:60-15981)

ANALYSIS

PME

The analysis is developed with inclusion of an energy dependence of the scattering time. It is asserted that this dependence is more significant than the anisotropy effects found in n-type silicon and germanium. (See 60G4.)

60G4 Grinberg, A. A.
THEORY OF PHOTOMAGNETIC EFFECT IN ANISOTROPIC CUBIC CRYSTALS
Soviet Phys. Solid State, vol. 2, pp. 1235-1242, January 1961.
(PA:60-15982)

ANALYSIS

PME

The effects of anisotropy are considered for the case of energy-independent scattering time. (See 60G3, 60R1, 66K2.)

60J1 Jacobs, H., A. P. Ramsa, and F. A. Brand
FURTHER CONSIDERATIONS OF BULK LIFETIME MEASUREMENT WITH A MICROWAVE ELECTRODELESS TECHNIQUE
Proc. IRE, vol. 48, pp. 229-233, February 1960. (EA:60-2152)

METHOD

PC-MICROWAVE

CONTACTLESS

SURFACE

This modification of an earlier technique (59R1) reduces the influence of surface recombination on the surface facing the incident light.

60L1 Larrabee, R. D.
MEASUREMENT OF SEMICONDUCTOR PROPERTIES THROUGH MICROWAVE ABSORPTION
RCA Rev., vol. 21, pp. 124-129, March 1960. (EA:60-4823)

METHOD

PCD-MICROWAVE ABSORPTION

CONTACTLESS

SPECIMEN SHAPING

Details of the apparatus required for this method are given. A minimum resistivity, below which the linear relationship between absorption and conductivity no longer holds, is specified in terms of specimen thickness and incident frequency.

60L2 Landsberg, E. G.
INFLUENCE OF GEOMETRICAL DIMENSIONS OF SAMPLES IN MEASUREMENTS OF DIFFUSION LENGTH USING THE PHOTOMAGNETIC METHOD
Soviet Phys. Solid State, vol. 2, pp. 777-781, November 1960.
(PA:60-15906)

EXPERIMENTAL

PC, PME

Experimental verification of the conditions for applicability of the formulas developed in 59M2 for partially illuminated specimens is reported.

60O1 Okazaki, S., and H. Oki
MEASUREMENT OF LIFETIME IN GERMANIUM FROM NOISE
Phys. Rev., vol. 118, pp. 1023-1024, May 15, 1960. (PA:60-9962)

METHOD

NOISE

Current noise, measured as a function of the position of an illuminated portion of the sample, is used to determine the lifetime of holes in n-type germanium.

60P1 Peattie, C. G., W. J. Odom, and E. D. Jackson
AN ULTRA-SHORT LIFETIME APPARATUS
Proc. IEE, Paper 3015E, January 1960, vol. 106B, Suppl. #15, pp. 303-307.
(EA:60-183)

EXPERIMENTAL

PCD

>0.01

LIGHT SOURCE

A high intensity source, consisting of a carbon arc and a front-surface mirror rotating at speeds up to 25,000 rpm, permits decay times as short as 10 ns to be measured.

60Q1 Quillet, A., and P. Gosar
SURFACE PHOTOVOLTAIC EFFECT IN SILICON
AND ITS APPLICATION TO THE MEASUREMENT
OF MINORITY CARRIER LIFETIME (In
French)
J. Phys. Radium, vol. 21, pp. 575-
578, July 1960. (PA:61-19860)

METHOD
SPV
SPECTRAL RESPONSE

Comparison with the travelling spot
method yielded good correlation. The method
is described more fully in 61G1 and 64B3.

60R1 Ravich, Yu. I.
CONCERNING THE THEORY OF THE PHOTO-
MAGNETOELECTRIC EFFECT IN SEMICON-
DUCTORS WITH COMPLEX ENERGY BANDS
Soviet Phys. Solid State, vol. 2,
pp. 2107-2110, April 1961.
(PA:61-1101)

ANALYSIS
PME

The effect of the ellipsoidal constant
energy surfaces in the conduction band of
germanium and silicon on the PME signal is
calculated. (See 60G4, 66K2.)

60R2 Ridley, B. K.
THE EFFECT OF AN ELECTRIC FIELD ON
THE DECAY OF EXCESS CARRIERS IN SEMI-
CONDUCTORS
Proc. Phys. Soc., vol. 75, pp. 157-
161, January 1960. (PA:60-9956)

ANALYSIS
PCD

An analysis of carrier sweep out and
its effect on the PCD curve is given for a
rectangular parallelepiped with zero surface
recombination velocity on the uncontacted
surfaces.

60S1 Sim, A. C.
THE DARK-SPOT METHOD FOR MEASURING
DIFFUSION CONSTANT AND LENGTH OF EX-
CESS CHARGE CARRIERS IN SEMICONDUCTORS
Proc. IEE, Paper 2997E, January 1960,
vol. 106B, Suppl. #15, pp. 311-328.
(PA:60-2857)

METHOD
DARK SPOT

The steady state version of this
method is a modification of the travelling
spot technique which, if considerable care
is taken, can yield a very precise measure-
ment of diffusion length. The transient
version yields the diffusion coefficient
directly. The paper is a very thorough
treatment of the method; it also has a
brief review of earlier work.

60S2 Subashiev, V. K., V. A. Petrusevich
and G. B. Dubrovskii
DETERMINATION OF THE RECOMBINATION
CONSTANTS FROM THE SPECTRAL RESPONSE
OF PHOTOCONDUCTIVITY
Soviet Phys., Solid State, vol. 2, pp.
925-926, November 1960. (PA:60-13634)

METHOD
PC
SPECTRAL RESPONSE

From measurements of photo signal as
a function of absorption coefficient for
two values of surface recombination velocity,
the diffusion length may be found.

60S3 Subashiev, V. K.
DETERMINATION OF RECOMBINATION PARA-
METERS FROM SPECTRAL RESPONSE OF A
PHOTOCELL WITH A p-n JUNCTION
Soviet Phys. Solid State, vol. 2, pp.
187-193, August 1960. (PA:60-15908)

ANALYSIS
JUNCTION PHOTOCURRENT
SPECTRAL RESPONSE

Relationships between diffusion length
and short circuit current are derived for
a variety of conditions.

60S4 Subashiev, V. K., G. B. Dubrovskii
and V. A. Petrusevich
DETERMINATION OF RECOMBINATION CONSTANT
AND THE DEPTH OF A p-n JUNCTION FROM
SPECTRAL CHARACTERISTICS OF A PHOTO-
CELL
Soviet Phys. Solid State, vol. 2, pp.
1781-1782, February 1961. (PA:60-18062)

ANALYSIS
JUNCTION PHOTOCURRENT
SPECTRAL RESPONSE

The diffusion length is obtained from
measurements of short-circuit current at two
wavelengths.

60V1 van Roosbroeck, W.
CURRENT CARRIER TRANSPORT AND PHOTO-
CONDUCTIVITY IN SEMICONDUCTORS WITH
TRAPPING
Phys. Rev., vol. 119, pp. 636-652,
July 15, 1960. (PA:60-13586)

ANALYSIS
PCD, PC, PME
S-R-H, TRAPPING

This comprehensive and thorough treat-
ment covers both transient and steady state
cases appropriate to the transport of in-
jected carriers. A more detailed and
extended discussion may be found in 60V2.

60V2 van Roosbroeck, W.
THEORY OF CURRENT CARRIER TRANSPORT
AND PHOTOCONDUCTIVITY IN SEMICON-
DUCTORS WITH TRAPPING
Bell Syst. Tech. J., vol. 39,
pp. 515-614, May 1960. (PA:60-13586)

ANALYSIS

PCD, PC, PME

S-R-H, TRAPPING

This extension of 60V1 thoroughly
details the theoretical basis for the
treatment.

60W1 Williams, R. L.
HIGH FREQUENCY LIGHT MODULATION
J. Sci. Instrum., vol. 37, pp. 205-
208, June 1960. (PA:60-8800)

PROCEDURE

PC(M)

>0.02

LIGHT SOURCE

A 180-face rotor, 1 inch in diameter,
suspended by a magnetic field in a vacuum
chamber is described. Simple optics and
an 80 W incandescent lamp are combined in
an f/2 system.

1961

61A1 Atwater, H. A.
MICROWAVE DETERMINATION OF SEMI-
CONDUCTOR CARRIER LIFETIMES
Proc. IRE, vol. 49, pp. 1440-1441,
September 1961. (EA:62-2551)

ANALYSIS

PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICRO-
WAVE

This correspondence considers the
impedance character of a semiconductor post
in a microwave transmission line (see
61J1) and suggests that the decay of the
microwave attenuation has the same time
constant as the decay of excess carrier
density only in special cases.

61B1 Bogdanov, S. V., and V. D. Kopylovskii
CONCERNING THE UTILIZATION OF THE
PHASE METHOD FOR MEASURING LIFETIME
OF NONEQUILIBRIUM CHARGE CARRIERS IN
SEMICONDUCTORS
Soviet Phys. Solid State, vol. 3,
pp. 674-679, September 1961.
(PA:61-17704)

ANALYSIS

PC(M)

PHASE SHIFT

A relatively complete discussion of
the relationship between phase shift and
lifetime is given for a variety of condi-
tions. (See 55S1, 57V1, 58L1.)

61B2 Berkovskii, F. M., S. M. Ryvkin, and
N. B. Strokan
EFFECT OF TRAPPING LEVELS ON THE DECAY
OF CURRENT THROUGH p-n JUNCTIONS
Soviet Phys. Solid State, vol. 3,
pp. 169-172, July 1961. (PA:61-12450)

ANALYSIS

PCD, JUNCTION PHOTOCURRENT DECAY

TRAPPING

It is shown that slow traps do not
produce long tails on the short circuit
current decay curves while they do on PCD
curves. On the other hand fast traps
produce long tails on both decay curves.

61D1 Dubrovskii, G. B.
DETERMINATION OF THE BASIC PARAMETERS
OF PHOTOVOLTAIC CELLS WITH p-n
JUNCTIONS WITH RESPECT TO THEIR
SPECTRAL CHARACTERISTICS
Industr. Lab., vol. 27, pp. 1236-1239,
April 1962.

METHOD

JUNCTION PHOTOCURRENT

SPECTRAL RESPONSE

To obtain the diffusion length and
hence the lifetime, measurements under other-
wise similar conditions are required for two
values of surface recombination velocity.

61F1 Fritzsche, C.
SURFACE AND GEOMETRICAL CORRECTIONS
FOR THE MEASUREMENT OF MINORITY
CARRIER LIFETIMES IN SEMICONDUCTORS
(In German)
Z. Angew. Phys., vol. 13, pp. 576-
580, December 1961. (PA:62-8347)

ANALYSIS

PCD, TRAVELLING SPOT

SURFACE TREATMENT (n-Ge, n-Si, p-Si)

Both bulk lifetime and surface
recombination velocity are discussed. A
table of surface recombination velocities
measured on a variety of etched germanium
and silicon surfaces is included.

61G1 Goodman, A. M.
A METHOD FOR THE MEASUREMENT OF SHORT
MINORITY CARRIER DIFFUSION LENGTHS
IN SEMICONDUCTORS
J. Appl. Phys., vol. 32, pp. 2550-
2552, December 1961. (PA:62-2131)

METHOD

SPV

SPECTRAL RESPONSE

The principles of the method, the
necessary apparatus, and various experimental
conditions are discussed briefly. (See 64B3
for a more detailed treatment in German.)

61H1 Harman, G. G., and R. L. Raybold
MEASUREMENT OF MINORITY CARRIER LIFE-
TIME IN SiC BY A NOVEL ELECTROLUMI-
NESCENT METHOD
J. Appl. Phys., vol. 32, pp. 1168-
1169, June 1961. (PA:61-11308)

METHOD
ELECTROLUMINESCENCE

The method described briefly is gen-
erally applicable to large-energy-gap semi-
conductors. The effect of trapping on the
method is considered qualitatively.

61H2 Hilsum, C., and B. Holeman
CARRIER LIFETIME IN GaAs
Proc. Int. Conf. Semiconductor Phys.,
(Prague, 1960), Academic Press, New
York, 1961, pp. 962-966. (PA:62-23389)

EXPERIMENTAL

PC, PME

RATIO

Trapping effects are taken into con-
sideration in the analysis of the data
described.

61H3 Holeman, B., and C. Hilsum
PHOTOCONDUCTIVITY IN SEMI-INSULATING
GALLIUM ARSENIDE
J. Phys. Chem. Solids, vol. 22, pp.
19-24, December 1961. (PA:62-8395)

EXPERIMENTAL

PCD, PC, PME

Details of techniques employed in
carrying out the measurements on high
impedance specimens are given.

61H4 Hyde, F. J., and H. J. Roberts
MINORITY CARRIER LIFETIME IN THE
BASE REGIONS OF TRANSISTORS
J. Electronics Control, vol. 11,
pp. 35-46, July 1961. (PA:62-4055)

EXPERIMENTAL

BASE TRANSPORT

Several related methods of measuring
effective lifetime in the base region are
compared with each other and with two
theories dealing with departures from a
one-dimensional analysis. Several
ambiguities remain.

61I1 Institute of Radio Engineers
MEASUREMENT OF MINORITY-CARRIER LIFE-
TIME IN GERMANIUM AND SILICON BY THE
METHOD OF PHOTOCONDUCTIVE DECAY
(IEEE Standard 225)
Proc. IRE, vol. 49, pp. 1292-1299,
August 1961.

STANDARD

PCD

SURFACE TREATMENT, OHMIC CONTACTS (n-Ge,
p-Ge, n-Si), SPECIMEN SHAPING,
LIGHT SOURCE

This standard method gives a detailed
procedure for performing the measurement
together with some background and inter-
pretive material. (See also 66A2.)

61J1 Jacobs, H.
MICROWAVE DETERMINATION OF SEMICON-
DUCTOR CARRIER LIFETIMES - AUTHOR'S
REPLY

Proc. IRE, vol. 49, pp. 1441-1442,
September 1961. (EA:62-2552)

ANALYSIS

PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICRO-
WAVE

In his reply to the criticism of 61A1,
the author points out an error and suggests
a distributed line approach rather than use
of lumped parameters in analyzing the micro-
wave absorption decay. (He develops this
approach more fully in 63J1.)

61K1 Ko, W. H.
THE REVERSE TRANSIENT BEHAVIOR OF
SEMICONDUCTOR JUNCTION DIODES
IRE Trans. Electron Devices, vol. ED-8,
pp. 123-131, March 1961. (EA:61-4012)

ANALYSIS

VOLTAGE DECAY, REVERSE RECOVERY, REVERSE
CURRENT DECAY

This general analysis of the reverse
diode transient also yields a relationship
between reverse recovery time and carrier
lifetime for forward pulses of arbitrary
length. An abrupt junction is assumed.

61L1 Loferski, J. J., and J. J. Wysocki
SPECTRAL RESPONSE OF PHOTOVOLTAIC
CELLS
RCA Rev., vol. 22, pp. 38-56, March
1961. (EA:61-4035)

EXPERIMENTAL

JUNCTION PHOTOCURRENT

SPECTRAL RESPONSE

Diffusion lengths of minority carriers
on both sides of the junction are deduced
from the spectral response of the junction
photocurrent.

61L2 Landsberg, E. G.
PHOTOMAGNETIC METHOD OF MEASURING THE
LIFETIME OF ELECTRONS AND HOLES
Industr. Lab., vol. 27, pp. 1226-1230,
April 1962.

METHOD
PC, PME
RATIO
LOW TEMPERATURE

Principles of the method and a cryostat for making measurements below room temperature are described. Trapping effects are considered.

61M1 Melehy, M. A., and W. Shockley
RESPONSE OF A p-n JUNCTION TO A
LINEARLY DECREASING CURRENT
IRE Trans. Electron Devices, vol.
ED-8, pp. 135-139, March 1961.
(EA:61-4013)

ANALYSIS
REVERSE RECOVERY

This novel variant employs a current which decreases linearly with time. The lifetime is related to the time interval between current and voltage zeros. (See also 63D2.)

61M2 Meier, A. A., E. A. Soldatov, and
V. P. Sushkov
SOME METHODS OF MEASURING LIFETIME OF
NONEQUILIBRIUM CHARGE CARRIERS BASED
ON THE MODULATION OF PHOTOCONDUCTIVITY
Industr. Lab., vol. 27, pp. 1223-1226,
April 1962. (CA:65-63-9190e)

METHOD
PC(M)
BRIDGE

Three modifications of the method are described; one is suitable for automated production control equipment.

61M3 Meier, A. A.
MEASUREMENT OF THE LOCAL DIFFUSION
LENGTH AND THE SURFACE RECOMBINATION
RATE WITH RESPECT TO TWO POINTS ON
SEMICONDUCTOR BARS
Industr. Lab., vol. 27, pp. 1230-
1235, April 1962.

METHOD
TRAVELLING SPOT

This modification of the method involves the use of data taken at only two points. (See 64M1 for an extension of the method.)

61N1 Nomura, K. C., and J. S. Blakemore
DECAY OF EXCESS CARRIERS IN SEMICONDUCTORS. II
Phys. Rev., vol. 121, pp. 734-740,
February 1, 1961. (PA:61-2406)

ANALYSIS
PCD
S-R-H, TRAPPING

The general treatment begun in 58N1 is continued.

61P1 Petrushevich, V. A., V. K. Subashiev,
and G. P. Morozov
AN INVESTIGATION OF GERMANIUM BASED
ON PHOTOELECTRIC METHODS
Soviet Phys. Solid State, vol. 3,
pp. 1091-1097, November 1961.
(PA:61-11325)

EXPERIMENTAL
PC, PME
SPECTRAL RESPONSE, RATIO
SURFACE TREATMENT (n-Ge, p-Ge), ABSORPTION
COEFFICIENT (Ge)

The method is outlined, and an analysis of data on a germanium specimen is presented. (See also 62P1, 63S1.)

61P2 Petrushevich, V. A.
PHOTOELECTRIC METHODS OF STUDYING
SEMICONDUCTORS
Industr. Lab., vol. 27, pp. 1217-1223,
April 1962.

REVIEW
PC, PME
SPECTRAL RESPONSE

In addition to a moderately detailed description of these methods, a wide variety of other methods are mentioned briefly. An extensive bibliography, principally of Russian literature, is included. The usefulness of the paper is reduced since not all symbols are defined clearly.

61P3 Petrushevich, V. A., O. V. Sorokin,
and V. I. Kruglov
CONCERNING THE APPLICABILITY OF "THE
EFFECTIVE SURFACE RECOMBINATION
PARAMETER" IN Ge AND Si.
Soviet Phys. Solid State, vol. 3,
pp. 1470-1475, January 1962.
(PA:62-10476)

EXPERIMENTAL
SURFACE TREATMENT (n-Ge, p-Ge, n-Si, p-Si)
SURFACE

It is shown that the "effective surface recombination velocity" concept is inapplicable under some conditions of high surface barriers which may occur in silicon. No cases of inapplicability were found for germanium.

61R1 Ravich, Yu. I.
DETERMINING THE CHARACTERISTIC PARAMETERS OF MINORITY CARRIERS IN SEMI-CONDUCTORS FROM MEASUREMENTS OF PHOTO-CONDUCTIVITY AND THE PHOTOMAGNETIC EFFECT
Soviet Phys. Solid State, vol. 3,
pp. 1162-1168, November 1961.
(PA:61-14426)

ANALYSIS

PC, PME

MULTIPLE LEVELS, TRAPPING

Calculations for cases where trapping is important, for cylindrical specimens (without trapping), and for nonlinear recombination processes are reported.

61R2 Romanov, V. A.
THE LIMITED APPLICABILITY OF THE CONCEPT OF UNIVERSAL SPEED OF SURFACE RECOMBINATION DURING THE INVESTIGATION OF KINETICS OF PHOTOELECTRICAL PROCESSES

Soviet Phys. Solid State, vol. 3,
pp. 23-25, July 1961. (PA:61-12460)

EXPERIMENTAL

PC(M), PME(M)

SURFACE

Differences in surface recombination are found for various conditions appropriate to PC and PME measurements.

61V1 Vogl, T. P., J. R. Hansen, and M. Garbuny
PHOTOCONDUCTIVE TIME CONSTANTS AND RELATED CHARACTERISTICS OF p-TYPE GOLD-DOPED GERMANIUM
J. Opt. Soc. Amer., vol. 51, pp. 70-75, January 1961. (PA:61-2425)

EXPERIMENTAL

PCD, NOISE

>0.01

LOW TEMPERATURE

Noise power and decay measurements are shown to give reasonable agreement for time constants around 10 ns. Experimental difficulties are discussed.

61W1 Weingarten, I. R., and M. Rothberg
RADIO-FREQUENCY CARRIER AND CAPACITIVE COUPLING PROCEDURES FOR RESISTIVITY AND LIFETIME MEASUREMENTS ON SILICON
J. Electrochem. Soc., vol. 108, pp. 167-171, February 1961. (PA:61-5020)

METHOD

PCD-Q

CONTACTLESS

A technique for use on long cylindrical pieces is described. (See 59K2, 65E2.)

1962

62A1 Adirovich, E. I., A. N. Gubkin, and B. D. Kopylovskii
MEASUREMENT OF SHORT LIFETIMES FROM PHASE CHARACTERISTICS OF THE VOLTAGE TRANSMISSION COEFFICIENT IN A CIRCUIT CONTAINING A p-n JUNCTION
Soviet Phys. Solid State, vol. 4,
pp. 1359-1365, January 1963.
(PA:62-23424)

METHOD

DIFFUSION CAPACITANCE

PHASE SHIFT

0.001-0.1

The method proposed in 59A2 is verified experimentally and limitations of the validity of the method are given.

62B1 Beattie, A. R., and R. W. Cunningham
LARGE-SIGNAL PHOTOMAGNETOELECTRIC EFFECT

Phys. Rev., vol. 125, pp. 533-540,
January 15, 1962. (PA:62-4074)

ANALYSIS

PME

An analysis of the PME effect for the case of injected carrier density greater than equilibrium minority carrier density shows that the lifetime is a function of injected carrier density. (See 64B1 for corrected curves.)

62B2 Boatright, A., W. A. Merkl, and H. L. Mette
HIGH PME SENSITIVITIES BY OPTICAL POLISHING OF Ge SURFACES
Rev. Sci. Instrum., vol. 33, pp. 1281-1282, November 1962. (PA:63-4956)

PROCEDURE

SURFACE TREATMENT (n-Ge, p-Ge)

A diamond-paste polishing process which yields a low recombination velocity on germanium surfaces is described.

62B3 Bauerlein, R.
MEASUREMENT OF SHORT CARRIER LIFETIMES IN SEMICONDUCTORS (In German)
Z. Angew. Phys., vol. 14, pp. 408-412,
July 1962. (PA:62-21127)

METHOD

BOMBARDMENT DECAY

ELECTRON INJECTION

~0.001

Improvements in the technique of 56W1 permit the measurement of shorter decay times.

62B4 Blakemore, J. S.
SEMICONDUCTOR STATISTICS
Pergamon Press, New York, 1962.

BOOK

PCD, PC

S-R-H, MULTIPLE LEVELS, TRAPPING, RADIATIVE
RECOMBINATION, AUGER EFFECT

The excellent book covers equilibrium and non-equilibrium statistics in a clear and thorough fashion. It is strongly recommended as the place to gain an understanding of recombination processes and the meaning of "lifetime."

62C1 Choo, S. C., and E. L. Heasell
TECHNIQUE FOR MEASURING SHORT CARRIER
LIFETIMES
Rev. Sci. Instrum., vol. 33, pp. 1331-
1334, December 1962. (PA:63-6579)

METHOD

PC(M)

PHASE SHIFT

>0.01

LOW TEMPERATURE, LIGHT SOURCE

Details of the method are clearly presented together with discussions of advantages over other methods (principally PCD) and difficulties which may be encountered.

62D1 Deb, S., and B. R. Nag
MEASUREMENT OF LIFETIME OF CARRIERS
IN SEMICONDUCTORS THROUGH MICROWAVE
REFLECTION
J. Appl. Phys., vol. 33, p. 1604,
April 1962. (PA:62-14528)

METHOD

PCD-MICROWAVE REFLECTION

CONTACTLESS

An arbitrarily shaped specimen may be used for this technique which is based on the dependence of microwave reflectivity on carrier density.

62H1 Howard, N. R.
A SIMPLE PULSE GENERATOR FOR SEMICON-
DUCTOR DIODE LIFETIME MEASUREMENTS
J. Sci. Instrum., vol. 39, pp. 647-648,
December 1962. (PA:63-12050)

PROCEDURE

VOLTAGE DECAY

0.1 - 100

PULSER

A simple pulse generator for use with the method is described.

62H2 Harten, H. U., and D. Polder
INFLUENCE OF A SURFACE SPACE-CHARGE
LAYER ON THE MOTION OF RECOMBINING
CARRIERS

Philips Res. Rep., vol. 17, pp. 125-
129, April 1962. (PA:62-23261)

MODEL

SURFACE

A model which accounts for the effect of an exhaustion layer on the motion of excess carriers is described. Since an accumulation layer is preferred in making lifetime measurement, this model would not generally be appropriate.

62K1 Kennedy, D. P.
REVERSE TRANSIENT CHARACTERISTICS
OF A p-n JUNCTION DIODE DUE TO
MINORITY CARRIER STORAGE
IRE Trans. Electron Devices, vol.
ED-9, pp. 174-182, March 1962.
(PA:62-16740)

ANALYSIS

REVERSE RECOVERY, REVERSE CURRENT DECAY

This analysis, primarily directed toward device design considerations, is appropriate to a narrow-base diode with a built-in field. Because of the variety of recovery mechanisms present, no simple relationship between recovery time and lifetime exists.

62K2 Krakauer, S. M.
HARMONIC GENERATION, RECTIFICATION,
AND LIFETIME EVALUATION WITH THE
STEP RECOVERY DIODE
Proc. IRE, vol. 50, pp. 1665-1676,
July 1962. (EA:62-12874)

METHOD

REVERSE RECOVERY

~0.001

Reverse recovery of a step recovery diode under sinusoidal voltage excitation is related to lifetime.

62M1 Muto, S. Y., and S. Wang
SWITCHING RESPONSE OF GRADED-BASE
p-n JUNCTION DIODES
IRE Trans. Electron Devices, vol.
ED-9, pp. 183-187, March 1962.
(PA:62-14569)

ANALYSIS

REVERSE RECOVERY, REVERSE CURRENT DECAY

In the graded-base diode, the excess carrier density nearest the junction is smaller than in a uniform-base diode with the same forward current; hence the recovery phase is shortened in the graded-base structure.

62N1 Nishizawa, J., Y. Yamoguchi, N. Shoji,
and Y. Tominaga
APPLICATION OF SIEMENS METHOD TO MEAS-
URE THE RESISTIVITY AND THE LIFETIME
OF SMALL SLICES OF SILICON
*Ultrapurification of Semiconductor
Materials*, MacMillan Co., New York,
1962, pp. 636-644. (PA:64-28568)

METHOD

PCD-Q

CONTACTLESS

This technique is suited for use with
small flat specimens. (See 67M2.)

62P1 Petrushevich, V. A.
DETERMINATION OF SEMICONDUCTOR PARA-
METERS BY PHOTOCONDUCTIVITY-COMPENSA-
TION OF THE PHOTOMAGNETIC EFFECT
Soviet Phys. Solid State, vol. 4,
pp. 337-339, August 1962.
(PA:62-18669)

ANALYSIS

PC, PME

SPECTRAL RESPONSE, RATIO

An initial analysis of the method is
given. It is shown that surface recombina-
tion velocity and diffusion length may be
independently determined. See 63S1 for a
modification of the analysis.

62R1 Ravich, Yu. I.
ON THE THEORY OF PHOTOMAGNETIC EFFECT
IN STRONG MAGNETIC FIELDS
Soviet Phys. Solid State, vol. 4,
pp. 1412-1418, January 1963,
(PA:62-23479)

ANALYSIS

PC, PME

RATIO

TRAPPING

The effect of a strong, non-quantizing
magnetic field on the PME and PC voltages
and on their ratio is calculated. Trapping
effects are also taken into account.

62R2 Rosenzweig, W.
DIFFUSION LENGTH MEASUREMENT BY MEANS
OF IONIZING RADIATION
Bell Syst. Tech. J., vol. 41, pp.
1573-1588, September 1962.
(EA:62-14298)

EXPERIMENTAL

JUNCTION PHOTOCURRENT

ELECTRON INJECTION, GAMMA SOURCE, PROTON
SOURCE

Measurements with an electron source,
gamma source, and proton sources are shown
to agree. The method and its limitations
are analyzed in some detail.

62S1 Suryan, G., and G. Susila
LIFETIME OF MINORITY CARRIERS IN SEMI-
CONDUCTORS: EXPERIMENTAL METHODS
J. Sci. Industr. Res., vol. 21A, pp.
235-246, May 1962. (PA:62-16694)

REVIEW

PCD, PCD-MICROWAVE ABSORPTION, PULSE DECAY,
PULSE DECAY-MICROWAVE, PC, PC-IR, PC-EDDY,
SPREADING RESISTANCE, PME, TRAVELLING SPOT,
FLYING SPOT, DRIFT FIELD, PULSE DELAY,
REVERSE CURRENT DECAY, NOISE, SPV DECAY

This review of methods is somewhat
superficial but does provide a reasonable
starting point. The PCD method is recom-
mended most strongly.

62S2 Swiderski, J.
*APPLICATION OF THE PHOTOVOLTAIC
EFFECT TO THE MEASUREMENT OF THE
DIFFUSION PATH LENGTHS OF MINORITY
CARRIERS ACROSS A TRANSISTOR CROSS-
SECTION (In Polish)
Przeglad Elektron., vol. 3, pp. 592-
594, 1962. (PA:64-7022)

METHOD

JUNCTION PV

62T1 Tauc, J.
PHOTO AND THERMOELECTRIC EFFECTS IN
SEMICONDUCTORS
Pergamon Press, New York, 1962.

BOOK

PC, PME, JUNCTION PV, BULK PV

This basic text emphasizes photo-
voltaic effects from a phenomenological
point of view. Other methods are discussed
briefly.

62V1 van der Maesen, F., C. A. A. J. Greebe,
and H. J. C. A. Nunnink
STEADY-STATE INJECTIONS IN SEMI-
CONDUCTORS
Philips Res. Rep., vol. 17, pp. 479-
512, October 1962. (PA:63-10751)

MODEL

S-R-H

Detailed models for both silicon and
germanium are discussed, but this theoret-
ical treatment is somewhat limited in scope.

62V2 van der Does de Bye, J. A. W.
TRANSIENT RECOMBINATION IN SILICON
CARBIDE
Philips Res. Rep., vol. 17, pp. 419-
430, October 1962. (PA:63-10840)

EXPERIMENTAL

BOMBARDMENT DECAY
ELECTRON INJECTION
0.0001-0.001

Some details of the experimental
arrangement and a discussion of the
sensitivity of the method are included.

62Z1 Zolotarev, V. F., and D. N. Nasledov
PHOTOMAGNETIC EMF IN p-TYPE InSb AT
ROOM TEMPERATURE IN AN ALTERNATING
MAGNETIC FIELD
Soviet Phys. Solid State, vol. 4,
pp. 1428-1431, January 1963.
(PA:62-23480)

METHOD
PME(M)

Increased sensitivity is claimed for
this method which employs an a-c magnet.
The complexity of the apparatus and analysis
makes it very difficult to apply in practice.

1963

63B1 Bhar, J. N.
MICROWAVE TECHNIQUES IN THE STUDY OF
SEMICONDUCTORS
Proc. IEEE, vol. 51, pp. 1623-1631,
November 1963. (PA:64-15531)

REVIEW

PCD-MICROWAVE REFLECTION, PCD-MICROWAVE
ABSORPTION
CONTACTLESS

Microwave techniques for measuring
semiconductor properties are reviewed
generally. Two methods of measuring carrier
lifetime are briefly discussed. (See 62D1,
60J1.)

63B2 Buimistrov, V. M.
THEORY OF THE PHOTODIFFUSION EFFECT
CAUSED BY A NONUNIFORM DISTRIBUTION
OF RECOMBINATION CENTERS
Soviet Phys. Solid State, vol. 5, pp.
351-356, August 1963. (PA:64-1674)

ANALYSIS
BULK PV

A rather hypothetical situation with
nonuniform concentration of deep-lying
recombination centers is proposed as a means
of determining the recombination properties
of the center. Unfortunately the voltage
expected from this effect is obscured by
other voltages in any practical case.
(See 65K1, 67E1.)

63C1 Cunningham, R. W.
APPARATUS FOR MEASUREMENT OF THE
PHOTOMAGNETOELECTRIC EFFECT
Rev. Sci. Instrum., vol. 34, pp. 83-88,
January 1963. (PA:63-7411)

METHOD
PME

Detailed information on the required
apparatus is supplied and a substitution
method for the measurement of short circuit
current is described.

63D1 Davies, L. W.
THE USE OF P-I-N STRUCTURES IN INVE-
STIGATION OF TRANSIENT RECOMBINATION
FROM HIGH INJECTION LEVELS IN SEMI-
CONDUCTORS
Proc. IEEE, vol. 51, pp. 1637-1642,
November 1963. (PA:64-15529)

METHOD
VOLTAGE DECAY
TRAPPING

This modification of the voltage decay
method permits study of lifetime at large
densities of injected carriers. The
influence of trapping on the decay curve is
observed in silicon.

63D2 Dlubac, J. J., S. C. Lee, and
M. A. Melehy
ON THE MEASUREMENT OF MINORITY CARRIER
LIFETIME IN p-n JUNCTIONS
Proc. IEEE, vol. 51, pp. 501-502,
March 1963. (PA:64-1626)

METHOD
REVERSE RECOVERY

A circuit which provides a linearly
decreasing current drive for a diode is
described. The lifetime may be found from
the time between the current and voltage
zeros. (See 61M1.)

63F1 Fortini, A., and J. P. Saint-Martin
PHOTOMAGNETO-ELECTRIC EFFECT IN
GRADED-GAP SEMICONDUCTORS
Phys. Status Solidi, vol. 3, pp. 1039-
1051, June 1963. (PA:63-17951)

ANALYSIS
PME

An analysis of the PME effect for a
one dimensional uniformly graded-gap semi-
conductor is given; the results of an
experiment on a strained germanium crystal
verify the analysis.

63F2 Figielski, T., and Z. Wieckowska
A SIMPLE PHOTOELECTRIC BRIDGE METHOD
FOR DETERMINING THE LIFETIME OF
INJECTED CURRENT CARRIERS IN SEMI-
CONDUCTORS
Acta Phys. Polon., vol. 24, pp. 675-
680, November 1963. (PA:64-22699)

METHOD
PC
BRIDGE
>10

A bridge technique suitable for use
on homogeneous bar specimens with ohmic
end contacts, a point contact, and a life-
time greater than 10 microseconds is
described.

63H1 Hashmi, S. Z. R.
MEASUREMENT OF LIFETIME OF MINORITY
CARRIERS BY CHRONOGRAPHIC TECHNIQUE
Indian J. Pure Appl. Phys., vol. 1,
p. 408, November 1963. (PA:64-6933)

METHOD
PULSE INJECTION-SWEEP OUT

A value for lifetime cannot be ob-
tained if this method which employs a
counter and scaler is carried out in the
manner described.

63J1 Jacobs, H., F. A. Brand, J. D. Meindl,
S. Weitz, R. Benjamin, and
D. A. Holmes
NEW MICROWAVE TECHNIQUES IN SURFACE
RECOMBINATION AND LIFETIME STUDIES
Proc. IEEE, vol. 51, pp. 581-592,
April 1963. (EA:63-6928)

METHOD
PCD-MICROWAVE REFLECTION, PCD-MICROWAVE
ABSORPTION
CONTACTLESS

Detailed analysis of the distributed
line approach to the microwave absorption
technique is followed by experimental
results on germanium and silicon.

63K1 Kolesnik, L. I., and Yu. A. Kontsevoi
SLOW CHANGES OF THE PHOTOELECTRO-
MAGNETIC EFFECT IN GERMANIUM
Soviet Phys. Solid State, vol. 5,
pp. 2454-2455, May 1964. (PA:64-10129)

EXPERIMENTAL
PME

A slow drift in the PME voltage was
observed under certain conditions on
plastically deformed samples. The problem
does not appear to be a general one.

63R1 Rose, A.
CONCEPTS IN PHOTOCONDUCTIVITY AND
ALLIED PROBLEMS
Interscience Publishers, New York,
1963.

BOOK
PC
TRAPPING

Although primarily concerned with the
field of insulators, this little monograph
contains an elegant discussion of recom-
bination and trapping centers which is highly
pertinent to the problem of steady-state
photoconductivity in semiconductors.

63S1 Subashiev, V. K.
DETERMINATION OF SEMICONDUCTOR
PARAMETERS FROM THE PHOTOMAGNETIC
EFFECT AND PHOTOCONDUCTIVITY
Soviet Phys. Solid State, vol. 5,
pp. 405-406, August 1963.
(PA:64-1585)

ANALYSIS
PC, PME
SPECTRAL RESPONSE, RATIO

It is shown that both the diffusion
length and surface recombination velocity
can be obtained from spectral response meas-
urements on specimens of two different
thicknesses. The work of 62P1 on thick
specimens is corrected.

63T1 Tang Pu-shan, Huo Ming-hsia,
Chen Tso-yu, and Wang Chu
*THE DIFFUSION LENGTH OF MINORITY
CARRIERS IN n-TYPE SILICON MEASURED
WITH A SURFACE BARRIER DETECTOR (In
Chinese)
Acta Phys. Sinica, vol. 19, pp. 448-
455, July 1963. (PA:64-4168)

EXPERIMENTAL
CHARGE COLLECTION EFFICIENCY
ALPHA SOURCE

63T2 Tateno, H., and K. Saito
*EFFECTS OF WAVEGUIDE PROPAGATION
CHARACTERISTICS ON THE MEASUREMENT
OF CARRIER LIFETIMES IN SEMICONDUCTORS
(In Japanese)
Bull. Electrotech. Lab., vol. 27,
pp. 49-60, March 1963. (PA:64-423)

ANALYSIS
PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICRO-
WAVE
CONTACTLESS

- 63W1 Wang Shou-wu
MEASUREMENT OF SEMICONDUCTOR MINORITY
CARRIER LIFETIMES BY OBSERVING THE
PHOTOCONDUCTIVE DECAY OF SPREADING
RESISTANCE UNDER A POINT CONTACT
(In Chinese)

Acta Phys. Sinica, vol. 19, pp. 176-
190, March 1963. (PA:64-1582)
Translation available from CFSTI:
AD-610 649.

METHOD

PCD-SPREADING RESISTANCE

The decay of carriers injected by a
flash of light is measured by a one probe
spreading resistance method. This method
gives results which compare satisfactorily
with ordinary PCD measurements and with
pulse-injection spreading resistance meas-
urements. More detail of the experimental
arrangement and limitations may be found
in 63Z1.

- 63Z1 Zhuang Wei-hwa and Pan Gui-sheng
MEASUREMENT OF THE LIFETIME OF MINOR-
ITY CURRENT CARRIERS IN Si AND Ge
BY OBSERVING THE PHOTOCONDUCTIVE
DECAY OF THE SPREADING RESISTANCE
UNDER A POINT CONTACT

Scientia Sinica, vol. 14, pp. 181-
192, February 1965. (PA:64-1610)

EXPERIMENTAL

PCD-SPREADING RESISTANCE

SURFACE TREATMENT (n-Ge, p-Ge, n-Si, p-Si)
SURFACE

Measurements on a variety of samples
support the analysis of this method given
in 63W1. The effects of surface recombina-
tion and wavelength of exciting light are
discussed in some detail.

1964

- 64A1 Adirovich, E. I., S. P. Lunezhev, and
Z. P. Mironenkova
MEASUREMENT OF 10^{-10} SEC RELAXATION
TIMES IN p-n JUNCTIONS BY THE PHASE
COMPENSATION METHOD
Soviet Phys. Dokl., vol. 9, pp. 999-
1002, May 1965. (PA:65-9691)

METHOD

DIFFUSION CAPACITANCE

PHASE SHIFT, BRIDGE

>0.0001

A bridge circuit which can be used for
measuring very short exponential time con-
stants is described in moderate detail.

- 64B1 Beattie, A. R., and R. W. Cunningham
LARGE-SIGNAL PHOTOCONDUCTIVE EFFECT
J. Appl. Phys., vol. 35, pp. 353-359,
February 1964. (PA:64-12989)

ANALYSIS

PC, PME

The PME and PC effects are analyzed for
large injected carrier density. Separate
majority carrier and minority carrier life-
times can be determined in the presence of
trapping.

- 64B2 Besfamil'naya, V. A., and
V. V. Ostroborodova
RECOMBINATION PROPERTIES OF SHALLOW
LEVELS OF GOLD AND COPPER IN p-TYPE
GERMANIUM, DETERMINED FROM THE NOISE
SPECTRUM

Soviet Phys. Solid State, vol. 6,
pp. 3005-3006, June 1965. (PA:66-
15622)

EXPERIMENTAL

NOISE

A brief description of the apparatus
and analysis appropriate to the method is
given in this short paper devoted primarily
to experimental results.

- 64B3 Bergmann, F., C. Fritzsche, and
H. D. Riccius
DETERMINATION OF DIFFUSION LENGTHS IN
SEMICONDUCTORS BY MEANS OF SURFACE
PHOTO EFFECTS (In German)
Telefunken Ztg., vol. 37, pp. 186-193,
November 1964. (EA:66-4060)

METHOD

SPV

SPECTRAL RESPONSE

ABSORPTION COEFFICIENT (Si, Ge, GaAs)

This paper is similar to 61G1 in method
and analysis. Absorption coefficients which
are essential in carrying out the method are
given.

- 64B4 Baev, I. A.
MEASUREMENTS OF THE MINORITY CARRIER
LIFETIME AND DIFFUSION COEFFICIENT
IN InSb BY THE MOVING-LIGHT-SPOT
METHOD

Soviet Phys. Solid State, vol. 6,
pp. 217-221, July 1964. (PA:64-30537)

METHOD

FLYING SPOT

Some details of the apparatus are
given; it is noted that the method is
sensitive to inhomogeneities in the crystal.

64D1 Daw, A. N., and N. K. D. Chowdhury
ON THE VARIATION OF THE LIFETIME OF
MINORITY CARRIERS IN A JUNCTION
TRANSISTOR WITH THE LEVEL OF INJECTION
Solid-State Electronics, vol. 7,
pp. 799-809, November 1964.
(PA:65-1671)

EXPERIMENTAL
VOLTAGE DECAY, BASE TRANSPORT
BRIDGE
TRAPPING

The effect of saturable traps in the transistor base on the voltage decay curve is discussed. There is also some speculation as to the origin of the traps which are not usually found in bulk germanium at room temperature.

64F1 Fink, H. J.
REVERSE RECOVERY TIME MEASUREMENTS
OF EPITAXIAL SILICON p-n JUNCTIONS
AT LOW TEMPERATURES
Solid-State Electronics, vol. 7, pp.
823-831, November 1964. (PA:65-1664)

EXPERIMENTAL
REVERSE RECOVERY
0.001-0.1
LOW TEMPERATURE

The reverse recovery time in these linearly-graded junctions is shown to depend on impurity gradient, injection level, and temperature.

64G1 Grove, A. S., and C. T. Sah
SIMPLE ANALYTICAL APPROXIMATIONS TO
THE SWITCHING TIMES IN NARROW-BASE
DIODES
Solid-State Electronics, vol. 7,
pp. 107-110, January 1964.
(PA:64-12936)

ANALYSIS
REVERSE RECOVERY

The recovery time of a narrow-base diode is shown to be independent of the lifetime.

64G2 Gräfe, W.
LIFETIME MEASUREMENTS ON SEMICONDUCTOR
SPECIMENS IN THE FORM OF SLICES (In
German)
Phys. Status Solidi, vol. 6, pp. K5-
K9, July 1964. (PA:65-12575)

ANALYSIS
PC(M), PME(M)
PHASE SHIFT

This extension of the method of 54G1 is suitable for use on thin slices with large surface recombination on the unilluminated surface.

64G3 Gutberlet-Vieweg, F.
METHODS FOR MEASUREMENT OF THE
CHARACTERISTICS OF SEMICONDUCTOR
SILICON IN THE FORM OF RODS OR SLICES
(In German)
Archiv. Techn. Messen, No. 340, pp.
109-112, May 1964. (EA:65-4009)

METHOD
PCD

An industrial measurement system is described. (See 66G1 for additional details and further discussion.)

64H1 Hoffmann, A., and K. Schuster
AN EXPERIMENTAL DETERMINATION OF THE
CARRIER LIFETIME IN p-i-n DIODES
FROM THE STORED CARRIER CHARGE
Solid-State Electronics, vol. 7, pp.
717-724, October 1964. (PA:64-30635)

METHOD
STORED CHARGE

Details of the apparatus necessary to measure stored charge in alloy diodes are given. (See 65S2 for extension to diffused diodes.)

64H2 Holmes, D. A., and D. L. Feucht
EXCESS CARRIER CONCENTRATION IN A BULK
SEMICONDUCTOR ILLUMINATED BY A PULSE
OF LIGHT
Proc. IEEE, vol. 52, p. 630, May 1964.
(EA:65-2319)

ANALYSIS
PCD-MICROWAVE ABSORPTION
CONTACTLESS

The transient solution for excess carrier density given in 63B1 is extended to include all time measured from the onset of a rectangular injection pulse of arbitrary duration. The authors recognise that this extension is not essential in lifetime determinations by the method.

64I1 Ishigame, M.
PEM EFFECT IN GERMANIUM
Japan J. Appl. Phys., vol. 3, pp. 250-
255, May 1964. (PA:64-26150)

EXPERIMENTAL
PME
PHOTON FLUX CALIBRATION
SURFACE

Apparatus and techniques used are described; spectral response curves for both PC and PME effect are discussed.

64I2 Ishigame, M.
PEM EFFECT IN SILICON
Japan J. Appl. Phys., vol. 3, pp. 720-
723, November 1964. (PA:65-4116)

EXPERIMENTAL

PME

ABSORPTION COEFFICIENT (Si)

Techniques necessary to apply the
method to silicon are described.

64I3 Ivanova, E. A., D. N. Nasledov, and
B. V. Tsarenkov
CARRIER LIFETIME IN THE SPACE-CHARGE
LAYER OF GaAs p-n JUNCTIONS
Soviet Phys. Solid State, vol. 6,
pp. 604-606, September 1964.
(PA:65-3901)

EXPERIMENTAL

I-V

Lifetime is deduced from the magnitude
of the g-r current in the forward direction;
care is taken to ensure that the g-r
component is the dominant one.

64I4 Il'yenkov, A. I., and Yu. A. Tkhoryk
*MEASUREMENT OF THE SHORT LIFETIMES
OF CURRENT CARRIERS IN SEMICONDUCTOR
DEVICES BY THE PULSE METHOD (In
Ukrainian)
Ukrayin. Fiz. Zh., vol. 9, pp. 139-149,
1964. (PA:64-17497)

ANALYSIS

REVERSE RECOVERY

A consideration of the effect of the
rise time of the pulse shows that it is
important when it is comparable with the
effective lifetime.

64J1 Jungk, G., and H. Menniger
ON THE MEASUREMENT OF THE DIFFUSION
LENGTH OF MINORITY CARRIERS IN SEMI-
CONDUCTORS (In German)
Phys. Status Solidi, vol. 5, pp. 169-
174, January 1964. (PA:64-22700)

METHOD

JUNCTION PHOTOCURRENT, JUNCTION PV

This method utilizes the collection
of carriers generated by strongly absorbed
light at a surface inclined at a small angle
to the collecting p-n junction. Diffusion
lengths down to 10 μm can be measured; the
method is adaptable to measurements on
epitaxial layers. A detailed analysis is
given in 64P2.

64M1 Meier, A. A., and R. Ya. Edemskaya
MEASURING DIFFUSION LENGTH IN SEMI-
CONDUCTORS BY THE DOUBLE LIGHT PROBE
METHOD

Industr. Lab., vol. 30, no. 2, pp. 255-
256, February 1964.

METHOD

TRAVELLING SPOT

COMPARATOR

This modification of the method in-
volves making measurements at two fixed
locations. The same light source split into
two beams is used to generate carriers.
The relative number of carriers is varied
by means of an automatically controlled
shutter in one of the beams. The system can
be made direct reading when the signal at
the collector contact is null.

64N1 Nilsson, N. G.
DETERMINATION OF CARRIER LIFETIME,
DIFFUSION LENGTH, AND SURFACE RECOM-
BINATION VELOCITY IN SEMICONDUCTORS
FROM PHOTO-EXCITED INFRARED
ABSORPTION

Solid-State Electronics, vol. 7, pp.
455-463, June 1964. (PA:64-22527)

ANALYSIS

PC(M)-IR

The method introduced in 59H2 is
analyzed in detail and applied to germanium.
Because the absorption cross section of holes
exceeds that of electrons in the wavelength
range used, hole lifetime is measured.
Effects of surface recombination and non-
uniform carrier generation are considered.

64P1 Pundur, P. A., and I. A. Feltyn'
*MEASURING OF THE LOCAL LIFETIME OF
MINORITY CARRIERS IN GERMANIUM (In
Russian)
Latv. PSR Zinat. Akad. Vestis, Fiz.
Tehn. Ser., No. 6, pp. 15-22, 1964.
(PA:65-15214)

EXPERIMENTAL

SPREADING RESISTANCE

Some conditions affecting the precision
of the measurement are given.

64P2 Puff, H.
PHOTOCURRENT IN A SEMICONDUCTOR WITH
A JUNCTION (In German)
Phys. Status Solidi, vol. 6, pp. 975-
990, September 1964. (PA:64-30654)

ANALYSIS

JUNCTION PHOTOCURRENT

This is a detailed analysis of the
method described in 64J1 and 65N1. The
limits of its applicability are described.

64R1 Ryvkin, S. M.
PHOTOELECTRIC EFFECTS IN SEMICONDUCTORS
Consultants Bureau, New York, 1964.

BOOK

PCD, PC, PME

S-R-H, MULTIPLE LEVELS, TRAPPING, RADIATIVE RECOMBINATION

This comprehensive text provides a good treatment of the subject, a detailed consideration of various meanings of the term "lifetime", and a summary of Russian work in the field.

64S1 Susila, G.
A METHOD FOR THE DETERMINATION OF SHORT LIFETIME OF CARRIERS IN A PHOTOCONDUCTOR FROM THE TRANSIENT PHOTORESPONSE
Indian J. Pure Appl. Phys., vol. 2, pp. 44-47, February 1964.
(PA:64-20429)

ANALYSIS

PCD

Calculations which take the decay time of the light source into account are given. These appear to be more general than those in 66P1.

64S2 Sushkov, V. P., and M. I. Iglitsyn
MEASUREMENT OF THE PHOTOGALVANO-MAGNETIC EFFECT IN SILICON SINGLE CRYSTALS
Soviet Phys. Solid State, vol. 6, pp. 2476-2480, April 1965.
(PA:65-18051)

EXPERIMENTAL

PC, PME

SURFACE TREATMENT (n-Si), OHMIC CONTACTS (n-Si), Light Source

Details for making these measurements on gold-doped silicon specimens are given.

64S3 Subashiev, V. K.
DETERMINATION OF THE QUANTUM YIELD OF THE INTERNAL PHOTOEFFECT FROM THE SPECTRAL DEPENDENCE OF PHOTOCONDUCTIVITY AND THE PHOTOMAGNETIC EFFECT
Soviet Phys. Solid State, vol. 6, pp. 1545-1548, January 1965.
(PA:65-12847)

METHOD

PC, PME

SPECTRAL RESPONSE

In addition to the quantum yield, the diffusion length may be found from the results of these experiments.

64V1 van Lint, V. A. J., and J. W. Harrity
CARRIER LIFETIME STUDIES IN HIGH-ENERGY IRRADIATED SILICON
Radiation Damage in Semiconductors, Academic Press, New York, 1964, pp. 417-423. (CA:66-65-11500a)

EXPERIMENTAL

BOMBARDMENT DECAY

ELECTRON INJECTION

S-R-H

An apparatus for injection of short (100 ns) pulses of high energy (30 MeV) electrons is briefly described.

1965

65B1 Baev, I. A., and E. G. Valyashko
AN INVESTIGATION OF THE DISTRIBUTION OF INHOMOGENEOUS REGIONS IN SEMICONDUCTORS
Soviet Phys. Solid State, vol. 7, pp. 2093-2099, March 1966.
(PA:66-15602)

METHOD

PC

The use of steady-state photoconductivity to determine the uniformity of the lifetime in bar-shaped specimens is described, but more emphasis is placed on resistivity variations.

65B2 Brosch, M., and H. Schaefer
DETERMINATION OF THE SPECTRAL DISTRIBUTION OF THE CARRIER LIFETIME DEDUCED FROM THE PME EFFECT AND PHOTOCONDUCTIVITY (In German)
Phys. Status Solidi, vol. 11, pp. K21-K24, September 1965. (PA:66-8360)

ANALYSIS

PC, PME

SPECTRAL RESPONSE, RATIO

A dependence of lifetime in germanium measured by the PME-PC ratio method on the wavelength of the incident illumination is reported in this short note.

65B3 Baranowski, J., and J. Mycielski
PEM AND NERNST EFFECTS IN MODULATED LIGHT
Phys. Status Solidi, vol. 9, pp. 91-96, April 1965. (PA:65-18034)

ANALYSIS

PME(M)

It is shown that the Nernst voltage can be neglected in comparison with the PME voltage in germanium and indium antimonide although it may become important in short lifetime, low thermal conductivity materials.

65C1 Curtis, O. L., Jr. and
R. C. Wickenhiser
AN EFFICIENT FLASH X-RAY FOR MINORITY
CARRIER LIFETIME MEASUREMENTS AND
OTHER RESEARCH PURPOSES
Proc. IEEE, vol. 53, pp. 1224-1225,
September 1965. (PA:66-12181)

METHOD

BOMBARDMENT DECAY

X-RAY SOURCE

Modifications to a commercial pulse
x-ray unit for use in this method are
described; use of this type of source is
convincingly advocated.

65E1 Evans, D. A., and P. T. Landsberg
THEORY OF THE DECAY OF EXCESS CARRIER
CONCENTRATIONS IN SEMICONDUCTORS
J. Phys. Chem. Solids, vol. 26,
pp. 315-327, February 1965.
(PA:65-12572)

MODEL

S-R-H, AUGER EFFECT, IMPACT IONIZATION

This paper presents a comprehensive
summary of the decay laws followed by excess
carriers in a variety of conditions. The
treatment is at an advanced level; a
thorough knowledge of elementary processes
is assumed.

65E2 Earlywine, E., L. P. Hilton, and
D. Townley
MEASURING THE PROPERTIES OF SEMICON-
DUCTOR GRADE MATERIALS
Semiconductor Prod. Solid State
Technol., vol. 8, pp. 17-30,
October 1965. (CA:66-64-125d)

METHOD

PCD-Q

CONTACTLESS

Industrial procedures for the measure-
ment of PCD lifetime and other important
parameters are outlined. (See 59K2, 61W1.)

65H1 Higuchi, H., and H. Tamura
MEASUREMENT OF THE LIFETIME OF MINOR-
ITY CARRIERS IN SEMICONDUCTORS WITH A
SCANNING ELECTRON MICROSCOPE
Japan J. Appl. Phys., vol. 4, pp.
316-317, April 1965. (PA:65-20369)

METHOD

TRAVELLING SPOT

ELECTRON INJECTION

The diffusion length is observed
directly by scanning an electron beam across
the edge of a p-n junction and displaying
the diode current on the z-axis (brightness)
in a TV-type raster sweep.

65K1 Kovtonyuk, N. F.
RECOMBINATION-GRADIENT PHOTO-EMF IN
SEMICONDUCTORS
Soviet Phys. Solid State, vol. 7,
pp. 1243-1244, November 1965.
(PA:66-15758)

EXPERIMENTAL

BULK PV

It is claimed that the photovoltage
predicted by 63B2 is observed. This claim
is disputed convincingly in 67E1.

65L1 Lemke, H.
ON THE PROBLEM OF LIFETIME MEASUREMENT
BY THE DOUBLE PULSE METHOD IN SILICON
SINGLE CRYSTALS (In German)
Phys. Status Solidi, vol. 12, pp.
115-123, November 1965. (PA:66-8542)

METHOD

PULSE DELAY

Extension of this technique to silicon
with resistivity greater than $1 \Omega \text{ cm}$ is
described.

65M1 McCormick, J. R., and H. K. Henisch
SIMPLE EQUIPMENT FOR LIFETIME MEASURE-
MENTS IN SEMICONDUCTORS
Amer. J. Phys., vol. 33, pp. 965-967,
November 1965. (PA:66-12325)

METHOD

PCD

A simple apparatus for making PCD
measurements is sketchily described. The
system includes a mirror rotating at
24,000 rpm. Though the apparatus is intend-
ed for use by non-specialist physics
teachers, sufficient detail to reproduce the
setup is not given. Sweep out and surface
recombination effects are discussed.

65M2 Mette, H. L., and A. Boatright
PHOTOMAGNETOELECTRIC EFFECT IN THIN
p-TYPE SILICON CRYSTALS
Phys. Rev., vol. 140, pp. A919-A922,
November 1, 1965. (PA:66-2416)

EXPERIMENTAL

PME

SURFACE TREATMENT (p-Si)

Though this paper is concerned
primarily with measurements of surface
recombination velocity, some of the infor-
mation on surface characteristics will be
useful in measurements of bulk lifetime.

65M3 Muratov, I. M.
ON THE PROBLEM OF DETERMINING THE
LIFETIME OF UNBALANCED CURRENT
CARRIERS
Radio Engng. Electronic Phys., vol.
10, pp. 132-135, January 1965.
(PA:65-30102)

ANALYSIS

REVERSE RECOVERY

The analysis is extended to include high injection levels; it is shown that the recovery time - lifetime relationship is not appreciably altered under many conditions.

65M4 Markowska, E., and J. Swiderski
APPLICATION OF LASER TO MEASUREMENTS
OF HOMOGENEITY AND DIFFUSION LENGTH
OF MINORITY CARRIERS IN SEMICONDUCTORS
Bull. Acad. Polon. Sci., Ser. Sci.
Tech., Electronique, vol. 13, pp.
39-42, March 1965. (EA:66-5850)

METHOD

SPV

SPECTRAL RESPONSE

Use of a laser is said to make possible the measurement of shorter diffusion lengths. Two lasers or a laser plus white light are required to carry out the measurement as described.

65N1 Norwood, M. H., and W. G. Hutchinson
DIFFUSION LENGTHS IN EPITAXIAL GALLIUM
ARSENIDE BY ANGLE LAPPED JUNCTION
METHOD

Solid-State Electronics, vol. 8,
pp. 807-811, October 1965.
(PA:66-8564)

EXPERIMENTAL

JUNCTION PHOTOCURRENT

The method described in 64J1 is discussed and applied to p-on-n GaAs epitaxial layers.

65S1 Suleiman, G. I., N. F. Kovtonyuk,
and D. T. Kokorev
AUTOMATIC APPARATUS FOR RECORDING
THE LIFETIME DISTRIBUTION OF NON-
EQUILIBRIUM CHARGE CARRIERS IN SEMI-
CONDUCTORS
Instrum. Exper. Tech., vol. 8,
pp. 203-205, January-February 1965.
(PA:66-2209)

METHOD

PC(M)

COMPARATOR

Automatic operation is achieved by balancing the PC signal at low frequency (attenuated by $\sqrt{2}$) with the signal at high frequency. At balance, this frequency equals the reciprocal lifetime, (See 59K1.)

65S2 Schuster, K.
DETERMINATION OF THE LIFETIME FROM THE
STORED CARRIER CHARGE IN DIFFUSED
p-s-n RECTIFIERS
Solid-State Electronics, vol. 8, pp.
427-430, April 1965. (PA:65-17979)

EXPERIMENTAL

STORED CHARGE

The technique outlined in 64H1 is extended to diffused diodes.

65S3 Swit, A.,
MEASUREMENT OF DIFFUSION LENGTH IN
SEMICONDUCTOR WAFERS
Bull. Acad. Polon. Sci., Ser. Sci
Tech., Electronique, vol. 13, pp.
31-38, March 1965. (PA:66-12324)

METHOD

DARK SPOT

A variant of the method of 60S1 is proposed, but many of the considerations discussed in the earlier paper are ignored.

65S4 Santha Kumari, K., and B. A. P. Tantry
MEASUREMENT OF LIFETIME OF MINORITY
CARRIERS IN JUNCTION TRANSISTORS
Indian J. Pure Appl. Phys., vol. 3,
pp. 380-384, October 1965.
(PA:66-8578)

EXPERIMENTAL

VOLTAGE DECAY, REVERSE RECOVERY, BASE TRANSPORT, COLLECTOR RESPONSE, BETA CUT- OFF FREQUENCY

It is shown experimentally on several commercial transistors that diode characteristic methods (with floating collector) give consistently lower values for lifetime than a transistor characteristic methods. The difference is explained on the basis of the different hole concentration at the collector in the two cases. (See 55G1.)

65S5 Swit, A.
MEASUREMENT OF DIFFUSION LENGTH OF
MINORITY CARRIERS IN THE REGION OF A
SEMICONDUCTOR WHEREIN THE CARRIERS ARE
GENERATED
Bull. Acad. Polon. Sci., Ser. Sci
Tech., Electronique, vol. 13, pp.
47-55, April 1965. (PA:66-5291)

METHOD

TRAVELLING SPOT

In this automated version of the method, an effective diffusion length in thin wafers is found by moving the collecting probe across a large but sharply delineated circular illuminated area. The method as described is not suitable for determination of bulk lifetime.

65V1 Vol'fson, A. A., S. M. Gorodetskii,
and V. K. Subashiev
A STUDY OF PHOTOCONDUCTIVITY IN
HEAVILY DOPED p-SILICON
Soviet Phys. Solid State, vol. 7,
pp. 53-57, July 1965. (PA:65-33448)

EXPERIMENTAL

PC

SPECTRAL RESPONSE

SPECIMEN SHAPING

TRAPPING

Two interesting ways to determine the
diffusion length from the spectral response
of the photoconductivity are described.

65V2 Vilms, J., and W. E. Spicer
QUANTUM EFFICIENCY AND RADIATIVE
LIFETIMES IN p-TYPE GALLIUM ARSENIDE
J. Appl. Phys., vol. 36, pp. 2815-
2821, September 1965. (PA:65-33674)

METHOD

SPV, PHOTOLUMINESCENCE

SPECTRAL RESPONSE

Spectral dependence of the photo-
luminescence and surface photovoltage are
shown to give values for diffusion length
which are in good agreement.

1966

66A1 Aukerman, L. W., and M. F. Millea
STEADY-STATE RECOMBINATION VIA
DONOR-ACCEPTOR PAIRS
Phys. Rev., vol. 148, pp. 759-765,
August 12, 1966. (PA:66-34450)

MODEL

PAIR RECOMBINATION

A phenomenological model is developed.
Similarities and differences with the S-R-H
model for recombination through single,
isolated defects are pointed out.

66A2 American Society for Testing and
Materials
STANDARD METHOD FOR MEASURING THE
MINORITY-CARRIER LIFETIME IN BULK
GERMANIUM AND SILICON (ASTM
Designation: F28-66)
ASTM Book of Standards, part 8, 1966.

STANDARD

PCD

SURFACE TREATMENT, OHMIC CONTACTS (n-Ge,
p-Ge, n-Si, p-Si), SPECIMEN SHAPING

This standard method was published
in preliminary form in 1963. It gives a
detailed procedure for performing the
measurement and assigns precision figures
for germanium and silicon. The procedure
is based in large part on that of 61I1.

66C1 Chilvers, P. W. C., and K. Foster
MEASUREMENT OF LIFETIME AND TRANSITION
TIME IN CHARGE STORAGE DIODES
Electronics Letters, vol. 2, pp. 108-
110, March 1966. (EA:66-9397)

METHOD

STORED CHARGE

0.025-0.25

A method of measurement of short life-
times in step-recovery diodes is given; fast
pulse equipment is not required.

66C2 Chaput, P., D. Blanc, E. Casanovas,
A. Peyre-Lavigne, A.-M. Chapuis, and
G. Soudain
CORRECT DETERMINATION OF LIFETIME FOR
MINORITY CARRIERS IN HIGH-RESISTIVITY
SILICON - MINIMAL THICKNESS NEEDED
(In French)
Electronics Letters, vol. 2, pp. 223-
224, June 1966. (EA:67-6206)

ANALYSIS

PME

SPECIMEN SHAPING

Conditions for minimum thickness of
specimens for PME measurements are developed
in this short letter. The value for 10,000
 Ω cm silicon appears to be questionable.

66C3 Coleman, J. A. and L. J. Swartzendruber
EFFECTIVE CHARGE CARRIER LIFETIME IN
SILICON p-i-n JUNCTION DETECTORS
IEEE Trans. Nuclear Sci., vol. NS-13,
pp. 240-244, June 1966. (PA:66-37487)

METHOD

CHARGE COLLECTION EFFICIENCY

ALPHA SOURCE

The method is described in some
detail without reference to earlier work.
(See also 59D2.) Correlation with PCD
measurements is not observed.

66D1 Davidson, L. A.
SIMPLE EXPRESSION FOR STORAGE TIME OF
ARBITRARY BASE DIODE
Solid-State Electronics, vol. 9,
pp. 1145-1147, November-December 1966.
(EA:67-2647)

ANALYSIS

REVERSE RECOVERY

A closed form for the ratio of life-
time to recovery time is given for arbitrary
base width. (See also 64G1.)

66F1 Fournier, M., and C. Lemyre
MEASUREMENT OF THE EFFECTIVE MINORITY
CARRIER LIFETIME IN THE FLOATING
REGION OF A P-N-P-N DEVICE
IEEE Trans. Electron Devices, vol.
ED-13, pp. 511-512, May 1966.
(PA:66-27807)

EXPERIMENTAL

REVERSE RECOVERY, ALPHA CUT-OFF FREQUENCY

By operating the SCR in the proper
mode, an alpha cut-off frequency can be
determined which yields lifetime directly.
Good correlation with reverse recovery
measurements is obtained.

66G1 Gutberlet-Vieweg, F.
IMPROVEMENTS IN THE d-c PHOTODECAY
METHOD FOR DETERMINATION OF MINORITY
CARRIER LIFETIME IN SILICON SINGLE
CRYSTALS (In German)
Archiv. Techn. Messen, No. 366,
pp. 151-154, July 1966.

METHOD

PCD

Various problems encountered in this
method are described and suitable conditions
for the measurement are discussed. The
effects of trapping are not considered in
detail.

66H1 Hung Gian
*THE MEASUREMENT OF EXCESS CARRIER
LIFETIME IN SEMICONDUCTORS BY PHOTO-
CONDUCTIVE PHASE-SHIFT OF SPREADING
RESISTANCE UNDER A POINT CONTACT
(In Chinese)
Acta Phys. Sinica, vol. 22, pp. 385-
403, April 1966. (PA:67-4839)

METHOD

PC(M)-SPREADING RESISTANCE

PHASE SHIFT

66I1 Ivanov, V. G.
RECOMBINATION IN HIGH RESISTIVITY
SILICON
Soviet Phys. Solid State, vol. 8,
pp. 1306-1307, November 1966.
(PA:67-4848)

EXPERIMENTAL

PCD

OHMIC CONTACTS (p-Si)

Some details of the techniques
employed are described in this short note.

66I2 Ivanov, V. G.
EFFECT OF SURFACE RECOMBINATION ON
PHOTOCONDUCTIVITY RELAXATION FOR
EXCITATION BY WEAKLY ABSORBED
RADIATION
Soviet Phys. Solid State, vol. 8,
pp. 2009-2010, February 1967.
(PA:67-15066)

EXPERIMENTAL

PCD

SURFACE TREATMENT (p-Si)

Spectral dependence of photoconduc-
tivity is reported on high resistivity
specimens treated in several ways; an
etchant which is described as producing
surfaces with low surface recombination
is not identified.

66J1 Jund, C., and R. Poirier
CARRIER CONCENTRATION AND MINORITY
CARRIER LIFETIME MEASUREMENT IN SEMI-
CONDUCTOR EPITAXIAL LAYERS BY THE MOS
CAPACITANCE METHOD
Solid-State Electronics, vol. 9,
pp. 315-319, April 1966.
(PA:66-21230)

METHOD

MOS CAPACITANCE

This relatively simple method is
satisfactory for both bulk and epitaxial
samples.

66K1 Kozhevin, V. E.
DISTRIBUTION OF THE CONDENSER PHOTO-
EMF ON THE SURFACE OF A SEMICONDUCTOR
Soviet Phys. Solid State, vol. 8,
pp. 1979-1980, February 1967.
(PA:67-15067)

METHOD

SPV

The importance of homogeneous surfaces
and the effects of surface recombination on
edge faces are discussed. In the experi-
ment, a small spot of light is swept over
the surface.

66K2 Kagan, Yu., and V. Sobakin
THEORY OF ANISOTROPIC PHOTOMAGNETO-
ELECTRIC EFFECTS IN GERMANIUM AND
SILICON TYPE SEMICONDUCTORS
J. Phys. Chem. Solids, vol. 27, pp.
597-609, March 1966. (PA:66-15756)

ANALYSIS

PME

The effects of anisotropy of the PME
effect are considered in detail for both n-
and p-type germanium. The square law depen-
dence on magnetic field is shown to be valid
only for low fields. Anisotropy effects are
more pronounced at 77 K than at 300 K.

66K3 Kuhn, A.
 RECOMBINATION LOSSES AND THEIR
 INFLUENCE ON THE ENERGY RESOLVING
 POWER OF p-i-n COUNTERS AND SOME
 MEASUREMENT METHODS FOR LIFETIME,
 MOBILITY AND HOMOGENEITY (In German)
 Czech. J. Phys., vol. B16, pp. 697-
 722, August 1966. (PA:66-37664)
 Translation available from Atomic
 Energy of Canada, Ltd., Chalk River,
 Ontario: AECL-2658.

EXPERIMENTAL

CHARGE COLLECTION EFFICIENCY

ELECTRON INJECTION, ALPHA SOURCE

This paper discusses the method
 briefly.

66M1 Munakata, C., and H. Todokoro
 A METHOD OF MEASURING LIFETIME FOR
 MINORITY CARRIERS INDUCED BY AN
 ELECTRON BEAM IN GERMANIUM
 Japan J. Appl. Phys., vol. 5, p. 249,
 March 1966. (PA:66-21241)

EXPERIMENTAL

CHARGE COLLECTION EFFICIENCY

ELECTRON INJECTION

The method is described very briefly;
 the reduction in lifetime below that
 determined by PCD measurements is attributed
 to surface recombination.

66M2 Munakata, C.
 MEASUREMENT OF MINORITY CARRIER LIFE-
 TIME WITH A NON-OHMIC CONTACT AND AN
 ELECTRON BEAM
 Microelectronics and Reliability,
 vol. 5, pp. 267-270, November 1966.
 (PA:67-7761)

METHOD

TRAVELLING SPOT

ELECTRON INJECTION

A small electron beam enables much
 shorter (50 μ m) diffusion lengths to be
 measured by this method.

66O1 Owen, D. B. B., and E. L. G. Wilkinson
 JUNCTION RECOVERY AND TRAPPING IN
 SILICON p⁺-n JUNCTIONS
 Internat. J. Electronics, vol. 20,
 pp. 21-29, January 1966. (PA:66-
 21432)

EXPERIMENTAL

REVERSE RECOVERY

TRAPPING

The effect of trapping on the measured
 recovery time is determined experimentally
 from measurements at different injection
 levels.

66P1 Penchina, C. M., and H. Levinstein
 MEASUREMENT OF LIFETIMES IN PHOTO-
 CONDUCTORS BY MEANS OF OPTICAL
 BEATING
 Infrared Phys., vol. 6, pp. 173-182,
 December 1966. (PA:67-20781)

METHOD

PCD, PC(M)

PHASE SHIFT

In addition to discussing a novel
 method using a laser source, this paper
 considers the effects of finite source decay
 time (see also 64S1) and of circuit para-
 meters on the PCD signal.

66S1 Streetman, B. G.
 CARRIER RECOMBINATION AND TRAPPING
 EFFECTS IN TRANSIENT PHOTOCONDUCTIVE
 DECAY MEASUREMENTS
 J. Appl. Phys., vol. 37, pp. 3137-
 3144, July 1966. (PA:66-31600)

ANALYSIS

PCD

S-R-H, TRAPPING

This clear analysis of the problem is
 very helpful in understanding recombination
 in the presence of minority carrier traps.

66S2 Santha Kumari, K., and B. A. P. Tantry
 RISE AND FALL TIMES OF TRANSISTORS IN
 SWITCHING OPERATION WITH FINITE
 IMPEDANCE
 Solid-State Electronics, vol. 9,
 pp. 730-733, July 1966. (EA:66-17088)

EXPERIMENTAL

COLLECTOR RESPONSE

The effect of circuit impedance on the
 relationship between lifetime and rise or
 fall times is considered.

66T1 Tada, H. Y.
 THEORETICAL ANALYSIS OF TRANSIENT
 SOLAR CELL RESPONSE AND MINORITY
 CARRIER LIFETIME
 J. Appl. Phys., vol. 37, pp. 4595-
 4596, November 1966. (PA:67-9333)

ANALYSIS

JUNCTION PHOTOCURRENT DECAY

The transient response of the short
 circuit current in a p-n junction is related
 to the bulk lifetime for certain conditions
 at the back contact. Recombination on other
 surfaces is neglected.

66T2 Thornton, P. R., K. A. Hughes,
D. V. Sulway, and R. C. Wayte
QUANTITATIVE MEASUREMENTS BY SCANNING
ELECTRON MICROSCOPY - I. THE USE OF
CONDUCTIVITY MAPS
Microelectronics and Reliability,
vol. 5, pp. 291-298, November 1966.
(PA:67-7987)

METHOD

TRAVELLING SPOT
ELECTRON INJECTION

An initial assessment of the use of
a scanning electron microscope for this
measurement is given.

66W1 Wang Chi-ming
*THE PHASE-SHIFT LIFETIME OF EXCESS
CARRIERS IN SEMICONDUCTORS UNDER
SINUSOIDAL INJECTION (In Chinese)
Acta Phys. Sinica, vol. 22, pp. 318-
324, March 1966. (PA:66-24135)

ANALYSIS

PC(M)
S-R-H

66Z1 Zakhvatikin, G. V., O. V. Karagioz,
V. N. Solomatin, and E. N. Gerasimov
DEVICE FOR MEASURING THE LIFETIME OF
CARRIERS IN HIGH-RESISTANCE SILICON
BY MEANS OF THE PHASE METHOD
Instrum. Exper. Tech., vol. 10,
pp. 444-448, March-April 1966.
(PA:67-17776)

METHOD

PC(M)
PHASE SHIFT, COMPARATOR
>1

Details of an improved apparatus
designed primarily for relatively long
lifetimes are given.

1967

67B1 Bilotti, A.
MEASUREMENT OF THE EFFECTIVE CARRIER
LIFETIME BY A DISTORTION TECHNIQUE
Solid-State Electronics, vol. 10,
pp. 445-448, May 1967. (PA:67-29654)

METHOD

DISTORTION

Distortion in the I-V characteristic
of a sinusoidally driven asymmetrical long
base diode without built-in fields occurs
below a certain critical frequency which
can be related to the carrier lifetime.

67D1 Dudenkova, A. V., and V. V. Nikitin
UTILIZATION OF A LASER TO MEASURE THE
LIFETIME OF EXCESS CARRIERS IN GALLIUM
ARSENIDE SINGLE CRYSTALS
Soviet Phys. Solid State, vol. 9,
pp. 664-665, September 1967.
(PA:67-20789)

METHOD

PC, PME

Some of the changes in recombination
processes encountered at the high injection
levels obtained when a laser is the source
of illumination are discussed in this short
note.

67E1 Esposito, R. M., J. J. Loferski, and
H. Flicker
CONCERNING THE POSSIBILITY OF OBSERV-
ING LIFETIME-GRADIENT AND DEPENDENT
PHOTOVOLTAGES IN SEMICONDUCTORS
J. Appl. Phys., vol. 38, pp. 825-831,
February 1967. (PA:67-26650)

EXPERIMENTAL

BULK PV

It is shown that the photovoltage
predicted by 63B2 cannot be observed if
ohmic contact is made to the specimen but
that it can be observed if capacitive
contacts are used. The findings of 65K1 are
disputed convincingly.

67H1 Heiman, F. P.
ON THE DETERMINATION OF MINORITY
CARRIER LIFETIME FROM THE TRANSIENT
RESPONSE OF AN MOS CAPACITOR
IEEE Trans. Electron Devices, vol.
ED-14, pp. 781-784, November 1967.
(PA:68-9179)

METHOD

MOS CAPACITANCE
CONTACTLESS
>0.0001

Measurements by this technique can be
made during wafer processing. Knowledge of
the resistivity of the specimen is required
in order to relate the response time to
carrier lifetime.

67H2 Hofstein, S. R.
MINORITY CARRIER LIFETIME DETERMINA-
TION FROM INVERSION LAYER TRANSIENT
RESPONSE
IEEE Trans. Electron Devices, vol.
ED-14, pp. 785-786, November 1967.
(PA:68-9177)

METHOD

MOS CAPACITANCE

The technique is modified so that the
influence of surface generated currents is
minimized.

67L1 Lichtenstein, R. M., and
H. J. Willard, Jr.
SIMPLE CONTACTLESS METHOD FOR MEASURING
DECAY TIME OF PHOTOCONDUCTIVITY IN
SILICON
Rev. Sci. Instrum., vol. 38, pp. 133-
134, January 1967. (PA:67-18071)

METHOD
PCD-EDDY
CONTACTLESS

Use of a slotted cage to absorb power
from the axial field extends the range of
the method to lower resistivity specimens.

67M1 McNeill, D. J.
MEASUREMENT OF MINORITY CARRIER LIFE-
TIME IN SEMICONDUCTOR JUNCTION DIODES
Amer. J. Phys., vol. 35, pp. 282-283,
March 1967. (PA:67-20780)

METHOD
VOLTAGE DECAY

A simplified form of the method suit-
able for teaching purposes is described.

67M2 Miyamoto, N., and J. Nishizawa
CONTACTLESS MEASUREMENT OF RESISTIVITY
OF SLICES OF SEMICONDUCTOR MATERIALS
Rev. Sci. Instrum., vol. 38, pp. 360-
367, March 1967. (PA:67-20937)

METHOD
PCD-Q
CONTACTLESS

Apparatus for making PCD measurements
in which the conductivity changes are
measured by a modified Q-meter technique is
described briefly. References are made to
earlier contactless resistivity measurement
methods. More details of the apparatus
and method for lifetime measurement may be
found in 62N1.

67W1 Wittry, D. B., and D. F. Kyser
MEASUREMENT OF DIFFUSION LENGTHS IN
DIRECT-GAP SEMICONDUCTORS BY ELECTRON-
BEAM EXCITATION
J. Appl. Phys., vol. 38, pp. 375-382,
January 1967. (PA:67-17753)

METHOD
CATHODOLUMINESCENCE
ELECTRON INJECTION

This method is similar to that of 65V2
but electron-beam excitation is substituted
for optical excitation.

67W2 Wilson, P. G.
RECOMBINATION IN SILICON p- π -n DIODES
Solid-State Electronics, vol. 10,
pp. 145-154, February 1967.
(PA:67-17773)

EXPERIMENTAL
VOLTAGE DECAY, REVERSE RECOVERY

Strong arguments favoring the voltage
decay method over the reverse recovery method
are convincingly presented.

NBS TECHNICAL PUBLICATIONS

PERIODICALS

JOURNAL OF RESEARCH reports National Bureau of Standards research and development in physics, mathematics, chemistry, and engineering. Comprehensive scientific papers give complete details of the work, including laboratory data, experimental procedures, and theoretical and mathematical analyses. Illustrated with photographs, drawings, and charts.

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