NBS 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

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# 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 photomagnetoelectric 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; photomagnetoelectric 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 Information (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 catagories: (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.

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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

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### REVIEW

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### BOOK

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## 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
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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

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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
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### 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

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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

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Method: 64H1, 66C1
Experimental: 65S2

### DISTORTION (Diode Current)

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Experimental: 65S4, 66S2

### ALPHA CUT-OFF FREQUENCY

Experimental: 66F1

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Experimental: 65S4

### MOS CAPACITANCE

Method: 66J1, 67H1, 67H2

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Method: 66C3
Analysis: 57V2
Experimental: 59D2, 63T1, 66K3, 66M1

NOISE

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

SPV DECAY

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BULK PV (Steady-State Bulk Photovoltage)

Analysis: 63B2

Experimental: 65K1, 67E1

Book: 62T1

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54G1, 55A3, 55S1, 56G1, 57E2, 57V1, 58G1, 58H2, 58L1, 59A2, 59K1, 59R2, 61B1, 62A1, 62C1, 64A1, 64G2, 66H1, 66P1, 66Z1

COMPARATOR

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

BRIDGE

54M1, 56E1, 58H1, 61M2, 63F2, 64A1, 64D1

SPECTRAL RESPONSE

56D1, 57G1, 59B2, 60B2, 60D2, 60Q1, 60S2, 60S3, 60S4, 61D1, 61G1, 61L1, 61P1, 61P2, 62P1, 63S1, 64B3, 64S3, 65B2, 65M4, 65V1, 65V2

RATIO

56G1, 56K1, 57B1, 58K1, 58Z1, 59A1, 59H1, 59M1, 60B2, 61H2, 61L2, 61P1, 62P1, 62R1, 63S1, 65B2

CONTACTLESS

56H1, 56H2, 57J1, 59K2, 59R1, 60D1, 60J1, 60L1, 61W1, 62D1, 62N1, 63B1, 63J1, 63T2, 64H2, 65E2, 67H1, 67L1, 67M2

ELECTRON INJECTION

56W1, 62B3, 62R2, 62V2, 64V1, 65H1, 66K3, 66M1, 66M2, 66T2, 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

Auxiliary Procedures and Data

SURFACE TREATMENT

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

### OHMIC CONTACTS

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

### SPECIMEN SHAPING

51H1, 56K1, 59R1, 60L1, 61I1, 65V1, 66A2, 66C2

### LOW TEMPERATURE Apparatus

55A1, 55P1, 56K1, 57R1, 58B6, 61L2, 61V1, 62C1, 64F1

### HIGH TEMPERATURE Apparatus

53H3, 57R1

### LIGHT SOURCE

56W2, 57G3, 58H2, 59R2, 60P1, 60W1, 61I1, 62C1, 64S2

### PHOTON FLUX CALIBRATION

59H1, 64I1

### PULSER

62H1

## Model for Recombination

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

Analysis: 56A1, 57C1, 57S1, 58N1, 60V1, 60V2, 61N1, 66S1, 66W1
Experimental: 55P1, 57R1, 58B3, 58S2, 64V1
Model: 52H1, 52S1, 57G2, 57S2, 58W1, 62V1, 65E1
Review: 57R2, 58A1, 58B5, 58M2
Book: 62B4, 64R1

### MULTIPLE LEVELS

Analysis: 59O1, 61R1
Experimental: 55P1, 58B3
Model: 56K2, 56L1, 57L1, 58B4, 58S1, 58W1
Review: 57R2
Book: 62B4, 64R1

### TRAPPING

Method: 63D1
Analysis: 56H3, 58L1, 58Z1, 59A1, 59M1, 59O1, 60G2, 60V1, 60V2, 61B2, 61N1, 61R1, 62R1, 66S1
Experimental: 53H2, 55H2, 55H3, 60G1, 64D1, 65V1, 66O1
Review: 55A2, 57R2, 58B5, 58M2
Book: 62B4, 63R1, 64R1

### PAIR RECOMBINATION

Model: 66A1

### BAND-TO-BAND RECOMBINATION

Model: 57L1

### RADIATIVE RECOMBINATION

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

### AUGER EFFECT

Model: 59B1, 65E1
Book: 62B4

## IMPACT IONIZATION

Model: 65E1

## SURFACE, Recombination

Method: 55S3, 56H4, 60J1
Analysis: 55S1, 56D1, 58L1, 58M1, 58R1, 58S3, 59B2, 60B1
Experimental: 61P3, 61R2, 63Z1, 64I1
Procedure: 59H3
Model: 62H2
Review: 58B5
Book: 50S1

## 4. Author Index

## 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--QUANTITATIVE STUDIES AND FILAMENTARY TRANSISTORS
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 LIFETIME 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 MEASUREMENTS
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 PROPERTIES 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 PHOTODIFFUSION 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.

## 1955

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 inlcude 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 PHOTOELECTROMAGNETIC 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 neglected 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 RECOMBINATION 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 indicated.

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 boundany 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.

## 1957

57A1 Armstrong, H. L.
**COMPARATOR METHOD FOR OPTICAL LIFETIME 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 expected 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 photoconductivity 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 LIFETIME 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 complicated 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 Semiconductors,* 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 circumstances 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 consisting 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 SEMICONDUCTOR 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 conditions 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 LIFETIMES 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 RESISTANCE 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 "lifetimes" 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 determination 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 different 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.)

## 1958

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 MEASUREMENTS
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 TRANSISTORS 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 LIFETIME 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 microseconds 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 PHOTOMAGNETOELECTRIC 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 cneter 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 devleoped for a multiple-charge-condition recombination cneter. 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 LIFETIMES 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 PHOTOELECTROMAGNETIC AND PHOTOCONDUCTIVE EFFECTS
Phys. Rev., vol. 112, pp. 852-855, November 1, 1958. (PA:59-4602)
ANALYSIS
PC, PME
RATIO
TRAPPING

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

## 1959

59A1 Amith, A.
PHOTOCONDUCTIVE AND PHOTOELECTROMAGNETIC 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 TRANSMISSION 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 complete than earlier ones. Comparisons with experimental results on InSb below room temperature are included.

59B2 Bir, L. G.
THE EFFECT OF SURFACE RECOMBINATION ON THE PHOTOCONDUCTIVITY OF SEMICONDUCTORS
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 conclusion 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 PHOTOVOLTAGE 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 illumation 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 LIFETIME AND SURFACE RECOMBINATION VELOCITY 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 μs is given. Extension to 10 ns is projected.

59K2 Keller, W.
HIGH FREQUENCY MEASUREMENT OF THE VOLUME 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 dimensional 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.)

59O1 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 results 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-MICROWAVE
CONTACTLESS
SPECIMEN SHAPING

This early paper describes the apparatus required for these measurements and considers 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 PHOTOELECTRIC 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 PHOTOCONDUCTIVITY DECAY MEASUREMENTS
Proc. IEE, Paper 2885E, May 1959, vol. 106B, Suppl. #15, pp. 308-310.
(PA:59-4573)
ANALYSIS
PCD

Relatively thick filters are recommended 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 considered. 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 distribution 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 LIFETIME 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 PARAMETERS FROM THE SPECTRAL RESPONSE OF A PHOTOCELL 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 Telecommunications*, 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 PHOTOCONDUCTIVITY 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 PHOTOMAGNETOELECTRIC EFFECT IN SEMICONDUCTORS 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 SEMICONDUCTORS
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 EXCESS 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 measurement 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 PARAMETERS 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 PHOTOCELL
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 PHOTOCONDUCTIVITY 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 treatment covers both transient and steady state cases appropriate to the transport of injected carriers. A more detailed and extended discussion may be found in 60V2.

60V2 van Roosbroeck, W.
THEORY OF CURRENT CARRIER TRANSPORT AND PHOTOCONDUCTIVITY IN SEMICONDUCTORS 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 SEMICONDUCTOR CARRIER LIFETIMES
Proc. IRE, vol. 49, pp. 1440-1441, September 1961. (EA:62-2551)
ANALYSIS
PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICROWAVE

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
CONTERNING 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 conditions. (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 otherwise 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 LIFETIME IN SiC BY A NOVEL ELECTROLUMINESCENT METHOD
J. Appl. Phys., vol. 32, pp. 1168-1169, June 1961. (PA:61-11308)
METHOD
ELECTROLUMINESCENCE

The method described briefly is generally applicable to large-energy-gap semiconductors. 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 consideration 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 LIFETIME 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 interpretive material. (See also 66A2.)

61J1 Jacobs, H.
MICROWAVE DETERMINATION OF SEMICONDUCTOR CARRIER LIFETIMES - AUTHOR'S REPLY
Proc. IRE, vol. 49, pp. 1441-1442, September 1961. (EA:62-2552)
ANALYSIS
PCD-MICROWAVE ABSORPTION, PULSE DECAY-MICROWAVE

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 microwave 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 Petrusevich, 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 Petrusevich, 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 Petrusevich, 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 SEMICONDUCTORS FROM MEASUREMENTS OF PHOTOCONDUCTIVITY 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 SEMICONDUCTOR 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 MEASURE 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 Petrusevich, V. A.
DETERMINATION OF SEMICONDUCTOR PARAMETERS BY PHOTOCONDUCTIVITY-COMPENSATION 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 recombination 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 in 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 SEMICONDUCTORS: 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 recommended 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 photovoltaic 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 SEMICONDUCTORS
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 theoretical 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 INVESTIGATION OF TRANSIENT RECOMBINATION FROM HIGH INJECTION LEVELS IN SEMICONDUCTORS
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 semiconductor 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 SEMICONDUCTORS
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 lifetime 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 obtained 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 PHOTOELECTROMAGNETIC 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 recombination 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 measurements 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-MICROWAVE
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 measurements. 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 MINORITY 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 recombination 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 constants 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 lifetimes 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, 164. (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 SEMICONDUCTORS (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 SEMICONDUCTORS 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 involves 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 RECOMBINATION 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 anlaysis 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 PHOTOGALVANOMAGNETIC 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 SEMICONDUCTOR 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 measurement of PCD lifetime and other important parameters are outlined. (See 59K2, 61W1.)

65H1 Higuchi, H., and H. Tamura
MEASUREMENT OF THE LIFETIME OF MINORITY 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 Ω cm is described.

65M1 McCormick, J. R., and H. K. Henisch
SIMPLE EQUIPMENT FOR LIFETIME MEASUREMENTS 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 intended 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 information 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 SEMICONDUCTORS
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. Ponon. 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 photoluminescence 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 phenomonological 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 lifetimes 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 lifetime 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 Deivces, 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 PHOTOCONDUCTIVE 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 photoconductivity 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 SEMICONDUCTOR 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 experiment, a small spot of light is swept over the surface.

66K2 Kagan, Yu., and V. Sobakin
THEORY OF ANISOTROPIC PHOTOMAGNETOELECTRIC 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 dependence 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 LIFETIME 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 μm) 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 PHOTOCONDUCTORS 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 parameters 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 levles 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 OBSERVING LIFETIME-GRADIENT AND DEMBER 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 DETERMINATION 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 LIFETIME 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 suitable 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-$\pi$-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.

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