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8-19-62-15

RADIATION EFFECTS ON SEMICONDUCTORS
AND SEMICONDUCTING MATERIALS:
AN ANNOTATED BIBLIOGRAPHY

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**RADIATION EFFECTS ON SEMICONDUCTORS
AND SEMICONDUCTING MATERIALS:
AN ANNOTATED BIBLIOGRAPHY**

Compiled by

HELEN B. McCORMICK

SPECIAL BIBLIOGRAPHY
SB-62-47

APRIL 1963

Work done in support of U.S. Air Force Contract AF 04(647)-787

Lockheed

MISSILES & SPACE COMPANY

A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION

SUNNYVALE, CALIFORNIA

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ABSTRACT

Radiation changes in semiconducting devices, materials and properties are reported here, along with some of the mechanisms by which these changes come about.

Part I is devoted to radiation effects as evidenced on specific semiconductor devices (diodes and transistors) and to a general treatment of semiconductors in the radiation environment. Part II deals with semiconducting materials as affected by radiation - changes in electrical, magnetic and optical properties; annealing of radiation damage and radiative recombination; electron spin resonance; photoconductivity induced by radiation. The semiconducting materials reported are germanium, silicon, and compound semiconducting materials, exclusive of the alkali halides. Organic semiconductors have not been included.

This selective bibliography reflects the technical literature issued during the time period of January 1960 - July 1962. Semiconductor devices as such have been given only general treatment, since the literature of semiconductor radiation changes is shown for specific spacecraft components and systems in a supporting bibliography covering the same time period: Radiation Changes in Spacecraft Systems, Components and Materials: An Annotated Bibliography, LMSC Special Bibliography SB-62-46, October 1962. (Available from ASTIA)

Closely related LMSC reports and special bibliographies are these:

SB-62-13, April 1962: Radiation Effects on Electronic Components: An Annotated Bibliography. Compiled by William L. Hollister. (AD 277-840)

Space Materials Handbook, by Claus G. Goetzel and John B. Singletary, editors
(For Official Use Only). Lockheed Missiles and Space Company, Sunnyvale,
California, January 1962. 523 pages. (Available from ASTIA)

SB-61-42, August 1961: Effects of Nuclear Radiation on the Optical, Electrical
and Thermophysical Properties of Solids: An Annotated Bibliography, compiled
by Robert C. Gex. (ASTIA AD-266 557)

SB-61-58, October 1961: Radiation Effects on Solar Cells and Glass: An Annotated
Bibliography, compiled by Alfred A. Beltran and Eugene E. Graziano. (AD 271-036)

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Part I

RADIATION EFFECTS ON SEMICONDUCTOR DEVICES:
DIODES AND TRANSISTORS

1. Almond, H. B.
FAST NEUTRON DAMAGE TO SELECTED
SEMICONDUCTOR DEVICES. Boeing Airplane
Company, Seattle, Washington. Rept. no.
D2-7427, 4 Oct 1960.

Seventeen types of transistor devices were investigated for permanent damage produced by fast neutrons, produced by the Godiva II reactor. The types of transistors tested ranged from a 15 ampere silicon power transistor to silicon and germanium high frequency tetrodes. Two special types, a C-35 silicon controlled rectifier and a 2N491 silicon unijunction were tested. Neutron dosimetry was performed using sulfur threshold dosimeters with the results being converted to equivalent plutonium dosimeter neutrons. Neutron dosage ranged from 1.76×10^{11} nvt to 7×10^{13} nvt.

The transistor data is presented in terms of β (small signal) versus I_e , β (large signal) versus I_e , I_{CO} versus neutrons/cm², and I_{CO} versus temperature.

2. Anderman, A.
THE EFFECTS OF NUCLEAR RADIATION ON
SEMICONDUCTOR MATERIALS AND DEVICES.
Atomics International, North American Aviation,
Inc., Canoga Park, Calif. Rept. no.
NAA-SR-MEMO-5556, 9 Aug 1960, 36p.

This report contains a review of the present body of knowledge concerning the effects of nuclear radiation on semiconductor devices, with primary emphasis placed on diodes, transistors and tunnel diodes.

3. Babcock, R. V.
Radiation damage to unipolar transistors.
In TRANSACTIONS OF THE AMERICAN
NUCLEAR SOCIETY, 1961 ANNUAL MEETING,
Pittsburgh, Pennsylvania, 4-8 Jun. Jun 1961.
4(1): 60-61.

Several experimental unipolar transistors developed by the Semiconductor Department of Westinghouse Electric Company were irradiated with fast (2-6 Mev) neutrons and with moderate energy *up to 600 kev) gamma radiation. The study indicated that unipolar transistors are potentially capable of greater radiation resistance than equivalent bipolar transistors and showed a serious ionization effect during gamma irradiation.

4. Babcock, R. , et al.
RESEARCH AND DEVELOPMENT OF
UNIPOLAR TRANSISTORS. Westinghouse
Electric Corporation, Dayton, Ohio.
Quarterly progress rept. through 15 Oct 1960.
Scientific rept. no. 6. (Contract AF 33(616)-6278).
ASTIA AD-246 018L.

Two unipolar and two bipolar transistors were exposed to 7×10^8 fast n/(cm² sec) and irradiation to a total fast neutron dosage (nvt) of 5×10^{13} /cm². Gamma and thermal neutron dosages were negligible: 1.5×10^5 R and less than 3×10^{10} thermal n/cm².

The following unipolar transistor parameters were observed periodically during irradiation: transconductance (g_m), current amplification factor (μ), saturation source current (I_{ss}), pinchoff voltage (W_0), channel resistance R_{ds} , and gate leakage current (I_g). The transport factor (β_{fe}) and collector leakage current (I_{co}) of the bipolar transistors were similarly measured. These were low frequency measurements (10 kc of D.C.). At longer intervals, g_m was measured as a function of frequency to determine the change in cut-off frequency. Sample temperatures and fast neutron flux were monitored continuously.

5. Backenstoss, G., Braunersreuther, E., and Gobel, K.
RADIATION DAMAGE OF SEMICONDUCTORS
BY PROTONS. European Organization for
Nuclear Research, Geneva. Rept. no.
CERN-62-5, 24 Jan 1962, 24p.

Ge and Si pnp and npn transistors and InAs and InSb Hall plates are exposed to proton irradiations at 550 to 600 Mev. The Hall plates are also exposed to 4-Mev protons. The transistor current amplification is affected at exposures of about 10^{12} protons/cm², and decreases to about 10% of its original value at 10^{13} protons/cm². At 10^{15} protons/cm² at 4 Mev, the minority carrier concentrations and mobilities in the Hall plates begin to be affected. Mobility losses as great as 90% are observed.

6. Barnett, H., et al.
REDUCED TiO₂ SEMICONDUCTOR APPLICATIONS.
University of New Mexico, Albuquerque, New Mexico.
Final rept. Rept. no. PR-23, Oct 1960. (Contract
DA-49-186-502-ORD-779).

TiO₂ point contact diodes were irradiated in the Godiva Reactor at LASL. The dosage received was approximately 5×10^{13} (n/cm²). The diode volt-ampere characteristics before and after irradiation are shown. It was felt that no appreciable neutron damage occurred and that the minor differences before and after irradiation are most likely attributable to measurements errors and differences in the room temperatures when the two measurements were made.

7. Baruch, P.
MOBILITY OF RADIATION-INDUCED DEFECTS
IN GERMANIUM: APPENDIX F. Bell Telephone
Laboratories, Inc., Whippany, New Jersey.
Fourth triannual technical note, 1 Mar-30 Jun
1960. Rept. no. WADD-TN-60-241, 15 Jul 1960,
p. 97-109. (Contract AF 33(616)-6235).

The samples used were indium alloy junction diodes or transistors made on 2.3 ohm-centimeter n-type Ge. The bare diodes were irradiated by a 1-Mev electron beam at liquid nitrogen or liquid freon (-30 C) temperatures; the encapsulated transistors were irradiated with Co-60 gamma rays at 35 C. In all cases the irradiation was carried to the point where the carrier concentration in the sample had decreased to 15 to 20 percent of its initial value.

8. Berger, A. G., Jr.
 Part 1, TRANSIENT EFFECTS IN SEMICONDUCTOR
 DIODES: APPENDIX VI. Boeing Airplane Co., Seattle,
 Washington, Wright Air Development Division, Com-
 munications Laboratory. Technical note 61-8; Boeing
 Document D2-7899, Jan 1961, p. 157-192. (Contract
 Nr AF 33(616)7531; Project Nr 0(1-5237); Transient
 Radiation Effects to Electronic Systems, Task no.
 42018). ASTIA AD-261 933.

Semiconductor devices were exposed to the neutron-plus-gamma radiation from the Kukla prompt-critical reactor, Lawrence Radiation Laboratory, Livermore, California, June 1960. The 1N277, gold-bonded germanium diode was selected for the testing procedures designed to yield circuit design parameters, and to develop preliminary circuit representation of the diode in a transient radiation environment. In deciding which circuit parameters to measure, the simple equivalent circuit approach was used. Measurements were made of current change at constant voltage, and voltage change at constant current, using simple resistor networks and batteries to set operating points for 1Ne77 diodes. Test procedures, setups, instrumentation and dosimetry are shown. Discussion of results and conclusions include: leakage corrections (for potting compound; resistor changes; battery voltage; cable leakage and photo effects; connector leakage and photo effects); transient radiation effects during diode forward conduction, and during reverse conduction; recommendations regarding leakage effects and effects of irradiation on diode characteristics.

9. Bertolotti, M.
 Effects of nuclear radiation on semiconductor
 devices. ALTA FREQUENZA
 30(9):631-42, Sep 1961. (In Italian)

Radiation damage, as a concept, is explained and illustrated. Effects of different types of nuclear radiation as they affect Ge and Si point contact and junction diodes are reviewed and backed by experimental results.

10. Bilinski, J. R. and Merrill, R.
Selecting transistors for radiation environments
ELECTRONICS 32(52):38-40, 25 Dec 1959.

How to predict the change in transistor current gain with nuclear radiation. Nomo-graphs also permit finding lifetime and tolerable neutron dosage for different transistor types.

11. Blair, R. R.
EFFECTS OF FAST NEUTRON BOMBARDMENT
ON TYPES 2N1675 AND PT901 SILICON POWER
TRANSISTORS: APPENDIX D. Bell Telephone
Laboratories, Inc., Whippany, New Jersey.
Sixth triannual technical note, 1 Nov 1960 -
28 Feb 1961. Rept. no. ASD-TN-61-81,
15 Mar 1961, p. 63-117.

The effects of fast-neutron bombardment on two types of silicon power transistors have been investigated. The first transistor was a Western Electric double-diffused npn type which had first the development number of 2082 and later the code number of 2N1675. Fifteen type-2082 transistors, which have selected base thicknesses ranging from 0.09 to 0.15 mil, and two PT901 transistors were exposed to a total fast-neutron flux of 3.2×10^{14} neutrons per cm^2 . Five transistors bearing the 2N1675 code number were subjected to an integrated flux of 2.1×10^{13} fast neutrons per cm^2 . The largest changes caused by bombardment with fast neutrons occur in α , the d-c current gain, and in the collector-emitter voltage drop in saturation for the 2082 - 2N1675 npn. Collector family $I_C - V_C$ curves exhibited loss of gain and increased saturation voltage with increasing Φ , but no loss of linearity of I_C versus I_B . Emitter breakdown voltage, $BVEBO$, was stable to at least $\Phi = 3.2 \times 10^{14}$ neutrons per cm^2 . Collector breakdown, $BVCBO$, was stable, to $\Phi = 1.8 \times 10^{13}$ neutrons per cm^2 but exhibited some rather large increase at $\Phi = 3.2 \times 10^{14}$ neutrons per cm^2 .

12. Blair, R. R. and Easley, J. W.
 FAST NEUTRON BOMBARDMENT BEHAVIOR
 OF GERMANIUM AND SILICON ESAKI DIODES:
 APPENDIX D. Bell Telephone Laboratories,
 Inc. Third triannual technical note, 1 Nov 1959 -
 15 Mar 1960. Rept. no. WADC-TN-60-160,
 15 Mar 1960, p. 37-65. (Contract AF 33(616)6235).

The experimental data reported show that the peak current is relatively insensitive to radiation damage, but the latter produces a large increase in the excess current. The magnitude of this increase is such that substantial increases in the valley current occur in the decade of exposure between 10^{16} and 10^{17} fast n/cm^2 for germanium units and in the decade between 10^{15} and 10^{16} fast n/cm^2 for silicon units.

13. Rohan, W. A., and Wager, A. J.
 Effects of steady state and pulsed nuclear
 radiation on GaAs tunnel diodes. In PROCEEDINGS
 OF THE INTERNATIONAL SYMPOSIUM ON AERO-
 SPACE NUCLEAR PROPULSION, Las Vegas,
 Nevada, 23-27 Oct 1961; IRE TRANS. ON
 NUCLEAR SCIENCE, NS-9:346-354, Jan 1962.

Studies were made on the utility of gallium arsenide tunnel diodes for equipment which must operate in both reactor and nuclear weapon environments. The results of experiments to determine the effects of radiation produced by steady-state and pulsed nuclear reactor on experimental tunnel diodes are described and compared with the theory governing tunnel diode behavior. It was concluded that current densities of at least 500 amp/cm should be maintained to minimize radiation effects. Results are presented in graph form.

14. Brown, W. L.
 TRANSIENT EFFECTS OF HIGH-INTENSITY
 RADIATION ON P-N JUNCTIONS: APPENDIX D.
 Bell Telephone Laboratories, Inc. Fifth
 triannual technical note, 1 Jul-31 Oct 1960.
 Rept. no. WADD-TN-61-17, 15 Nov 1960,
 p. 57-63. (Contract AF 33(616)6235).

This paper considers the transient in current and in temperature which result from the generation of hole electron pairs by high intensity ionizing radiation in a reversed biased p-n junction. The treatment is reasonably exact and considers two major cases. The first is the response to a step function of radiation turned on at time zero, and the second is the response to a pulse of duration, t_p , which may be either short or long compared with the recombination lifetime, τ , in the junction region. First the junction current and then the temperature will be considered for these two cases.

15. Byer, A.
 NUCLEAR RADIATION RESISTANT POWER
 TRANSISTORS. Philco Corporation, Lansdale
 Division, Lansdale, Pennsylvania. Final rept.,
 15 May 1959-14 Jul 1960. Rept. no. R109-DF.
 (Contract DA-36-039-SC-78307).

The Micro Alloy Diffused-Base Transistor (MADT) technology was used to develop the Radiation Resistant Power Transistor SCL-700222. The device is a 15 watt, high frequency germanium, power transistor capable of withstanding irradiation up to 10^{14} fast n/cm². Although the characteristics of the unit degrade slightly at the 10^{14} level, it has been shown that the unit is not severely affected until a level of 5×10^{14} is reached.

16. Chandler, H. G.
EFFECTS OF PULSED NUCLEAR RADIATION
ON NONOPERATING TUBES AND TRANSISTORS.
Diamond Ordnance Fuze Laboratories. Rept. no.
TR-705, 20 Nov 1959. (Contract DA-506-01-001).

During Operation Hardtack, electron tubes of both ceramic and glass construction and transistors were exposed to nuclear radiation while they were not functioning. These components were subjected to neutron bombardment as great as 4×10^{14} Pu²³⁹ nvt. No deleterious effects on the electron tubes were observed under these conditions. However, measured transistor parameters suffered large percentage changes from radiation greater than 3×10^{13} Pu²³⁹ nvt. These effects were much greater in audio than in r-f types.

17. De Nure, D. G. and Blair, R. R.
EFFECTS OF FAST NEUTRON BOMBARDMENT
ON TYPES 2N1060 and 2N1060E SILICON
SWITCHING TRANSISTORS: APPENDIX D.
Bell Telephone Laboratories, Inc., New York,
N. Y. Seventh triannual technical note, Mar 1-
30 Jun 1961. Rept. no. ASD-TN-61-137,
15 Jul 1961, p. 47-60. (Contract AF 33(616)6235).

The effects of fast-neutron bombardment on Western Electric 2N1060 and 2N1060E transistors have been investigated. The 2N1060 transistor is used for small signal switching applications in the computer field and for small signal amplification. Ten transistors of each type were exposed to a fast-neutron flux of 2.2×10^{14} neutrons per cm². The 2N1060E transistor was determined to be more radiation resistant than the 2N1060 type. This difference is approximately that which could be expected from the thinner base region used in the epitaxial type.

18. Denney, J. M. and Downing, R. G.
CHARGED PARTICLE RADIATION DAMAGE
IN SEMICONDUCTORS. I. EXPERIMENTAL
PROTON IRRADIATION OF SOLAR CELLS.
Space Technology Laboratories, Inc., Los Angeles.
Final rept. Rept. no. 8987-0001-RU-000,
15 Sep 1961, 51p. (Contract NAS5-613).

19. Easley, J. W. and Blair, R. R.
Fast neutron bombardment of germanium and
silicon Esaki diodes. JOURNAL OF APPLIED
PHYSICS 31(10):1772-74, Oct 1960.

The fast neutron irradiation behavior of germanium and silicon Esaki diodes has been experimentally examined. The dominant change produced is an increase in the excess current which is proportional to integrated neutron flux. The observed increase in the vicinity of the current minimum is approximately 2.6×10^{-15} amp/fast neutron and 1.1×10^{-14} amp/fast neutron for germanium and silicon diodes respectively. Substantial changes result in the voltage current characteristics of the diodes employed in the decade of exposure between 10^{16} and 10^{17} fast n/cm² for germanium diodes and between 10^{15} - 10^{16} fast n/cm for silicone diodes. One kilomegacycle cavity oscillators employing germanium diodes exhibit a marked reduction in power output in the decade of exposure between 10^{16} - 10^{17} fast n/cm². The magnitude of the decrease is in approximate agreement with the observed bombardment reduction of diode negative conductance.

20. Easley, J. W., and Blair, R. R.
TRANSIENT PHENOMENA IN SEMICONDUCTOR
DEVICES: APPENDIX E. Bell Telephone
Laboratories, Inc., Whippany, New Jersey.
Third triannual technical note, 1 Nov 1959 -
29 Feb 1960. Rept. no. WADC-TN-60-160,
15 Mar 1960, p. 57-68. (Contract AF 33(616)6235).

An examination has been made of the effect on certain electronic components of pulsed gamma ray and neutron radiation as obtained from the Godiva II reactor. The components included silicon diodes, silicon and germanium transistors, tantalum capacitors and coaxial polyethylene dielectric cable. The peak intensities of the radiation pulse at the component locations were in the vicinity of 2×10^7 r/sec of gamma-rays and 2×10^{16} fast n cm⁻² sec⁻¹ in terms of neutrons with energy greater than 2.5 Mev. The greater portion of the measurements concerned the pulse of ionization current which traverses a semiconductor junction when the device is exposed to a high intensity burst of radiation.

21. Furukawa, Y.
Effect of neutron radiation on characteristics
of Esaki diodes. J. INST. COMMUN. ENGRS.
JAPAN 44(8):1185-1190, Aug 1961.
(In Japanese)

V-I characteristics were measured at various stages of the irradiation (up to a total flux of 2×10^{16} cm² in the TOKAI reactor). Results indicated that excess current at fixed bias voltages increases linearly with total neutron flux O.

22. Gardner, L. and Kaufman, A. B.
SEMICONDUCTORS IN A HYPERNUCLEAR
ENVIRONMENT. Litton Systems, Inc.,
Woodland Hills, Calif. Rept. no. ASD TN 61-1000.
(Contract AF 33(600)41452; Project 8222).
ASTIA AD-267 324.

Operating characteristics of different types of transistors and diodes were examined during their exposure to a hypernuclear environment. They were selected on the basis of high alpha cutoff frequency, small base width, and low resistivity, and included both silicon and germanium NPN and PNP types. This total integrated exposure was accumulated during 100 hours in the GTR (Ground Test Reactor) facility. The purpose was to find semiconductor devices suitable for application within a servoamplifier used as part of Litton's NGL inertial guidance platform. Characteristics which were of interest were the dc and ac beta at 400 c and the low collector currents as a function of exposure to the nuclear environment. All semiconductors tested and their observed characteristics before, during, and after irradiation are discussed.

23. Hamre, H. G., et al.
SEMICONDUCTOR DIODE PERFORMANCE IN
NUCLEAR RADIATION ENVIRONMENTS.
Armour Research Foundation, Illinois Institute
of Technology, Chicago, Illinois. Interim
scientific rept. no. 1, 15 Apr-15 Nov 1960.
(Contract AF 33(616)7239).

The purpose of this investigation is to determine the effect of steady-state fast neutron radiation on the performance characteristics of six types of microwave diodes and two types of general purpose diodes. Diodes to be studied are general

purpose types (1N464 (Silicon junction) and 1N127 (Germanium point-contact), and microwave diode types 1N25, 1N23B, 1N21WE, 1N23WE, 1N263, and 1N3096R. Two full scale reactor runs of 1000 hours each at a flux level equal to or greater than 10^{10} nv are planned.

Preliminary experiments on diodes, cabling and associated equipment have been conducted in the high flux area of the reactor to verify instrumentation techniques and to establish guidelines for the 1000 hour tests. Results suggest that some of the microwave diodes may last to nearly the full 1000 hours; in general, general purpose diodes degraded faster than the microwave diodes.

24. How radiation affects tunnel diodes.
ELECTRONICS
33(19):32-33, May 1960.

Researchers at three companies report on severe degradation of tunnel diodes characteristics by exposure to nuclear radiation of the order of 10^{17} fast neutrons/cm².

25. Hulten, W. C.
Radiation effects of 40 and 400 mev protons on transistors. In SYMPOSIUM ON EFFECTS OF SPACE ENVIRONMENT ON MATERIALS, Society of Aerospace Material and Process Engineers, St. Louis, Missouri, 7-9 May 1962. 42p.
St. Louis, published courtesy of McDonnell Aircraft Corporation, 1962.

Experimental results covering the data collected before, during, and after the bombardment of several types of transistors with 40 and 440 mev protons. The data indicate a proton energy, as well as a transistor frequency dependence on degradation of the various parameters measured. A number of figures are presented showing the degradation of the gain of the transistors as a function of integrated proton flux.

26. Hunter, E. T.
 THE USE OF PLASTIC SHIELDS TO REDUCE
 PERMANENT NUCLEAR RADIATION
 DAMAGE. U. S. Army Signal Research and
 Development Laboratory, Fort Monmouth,
 New Jersey. Rept. no. USASRDL-TR2123,
 15 Jun 1960. ASTIA AD-239157.

Permanent alteration in DC electrical characteristics of germanium, homogeneous base, pnp, power transistors was determined as a function of the thickness of epoxy-type shielding material surrounding the device. Exposures were made at the Godiva reactor.

Results indicate that most of the permanent damage is caused by fast neutrons, with a smaller part of the damage caused by some other component of the radiation, and that the epoxy shields thermalize many of the fast neutrons, thereby reducing the permanent damage suffered by the transistors.

27. Innes, R.
 Radiation and other environmental effects on
 satellites. JOURNAL OF BRITISH INSTITU-
 TION OF RADIO ENGINEERS 22(3):249-250.
 Sep 1961. (Presented by the Conference on
 Radio Techniques and Space Research, Oxford,
 England, 5-8 Jul 1961).

Included here are a description of the environmental hazards of space flight, with a view toward design of more reliable operating equipment. Radiation effect on equipment is preceded by a detailed explanation of potential damage resulting from the breakdown of high energy radiation on meeting matter, the mechanism of radiation damage, and the exposure necessary to cause malfunction of satellite electronic equipment. Since semiconductors are considered the most susceptible to damage, the author has concentrated on the expected decay of transistors as governing the reliability of electronic equipment. Estimates are made of expected transistor life and suggestions given for the design of circuitry affording wide tolerance to transistor parameters. Short circuiting, erosion, corrosion, and influence of the magnetic field are also represented as hazards in the satellite environment.

28. Jones, J. P.
**ELECTRON BOMBARDMENT OF THE
 SILICON UNIPOLAR TRANSISTOR.**
 Thesis submitted to the Faculty of the
 School of Engineering of the Air Force
 Institute of Technology, Air University,
 Wright-Patterson AFB, Ohio. Rept. no.
 GE/EE/60-7, Aug 1960. ASTIA AD-246 101.

Three experimental Westinghouse silicon unipolar transistors were subjected to 1 Mev electrons and a pictorial record was obtained of the static characteristics of each device as the irradiation damage progressed. The investigation determined that the silicon unipolar transistor does not offer any significant advantage over the bi-polar transistor for circuit applications where resistance to radiation is an important factor. Short summaries of unipolar transistor theory and electron damage to n-type silicon are included in the report.

29. Kavipurapu Sri Ram
**MINORITY CARRIER LIFETIME MEASURE-
 MENTS IN NEUTRON-IRRADIATED SILICON
 DIODES: APPENDIX C.** Bell Telephone
 Laboratories, Inc. Sixth triannual technical
 note, 1 Nov 1960-28 Feb 1961. Rept. no.
 ASD-TN-61-81, 15 Mar 1961, p. 35-60.

Silicon junction diodes of the type 1N462, 1N463, and 1N486A were investigated for radiation damage. Minority carrier lifetimes were measured by the junction recovery method. The constant of proportionality, a , in the relation $T_0 \phi = a$, has been obtained in all three cases.

30.

Knox, W. P.

EFFECTS OF COBALT 60 GAMMA RAY ON
LOW-MELTING, GLASS-COATED SILICON

DIODES: APPENDIX E. Bell Telephone

Laboratories, Inc., Whippany, New Jersey.

Eighth triannual technical note, 1 Jul-31 Oct

1961. Rept. no. ASD-TR-62-189, 15 Nov 1961,

101p. (Contract AF 33(616)6235).

An irradiation was performed at the Brookhaven National Laboratories gamma facility to determine the effect of 9.4×10^7 roentgen gamma rays on several 56-volt experimental silicon diodes coated with different types of low-melting glass systems. The following measurements were made concurrent with gamma irradiation. (1) diode reverse current (2) forward voltage current characteristic (3) reverse voltage current characteristic. There was essentially no change in the forward and reverse breakdown voltages for all three types of devices tested in this experiment. There was an immediate increase in reverse bias current for all three units, and this persisted during the period they were in the gamma field. During the irradiation, no significant change in the reverse current was observed. The iodine glass-coated device had poor reverse characteristics to begin with and showed considerable instability during the test. It was concluded that there was no significant permanent damage to the devices due to a gamma dose at the rate specified above.

31.

Knox, W. P.

RADIATION DAMAGE ANNEALING BY

LOW-ENERGY ELECTRONS: APPENDIX B.

Bell Telephone Laboratories, Inc. Fifth

triannual technical note, 1 Jul-30 Oct 1960.

Rept. no. WADD-TN-61-17, 15 Nov 1960,

p. 31-44. (Contract AF 33(616)6235).

To investigate the possibility of annealing neutron-induced damage defects in semiconductors by unidirectional low-energy electron radiation, an experiment was performed using the electron beam of a Van de Graaff accelerator. The 2N-1051 double-diffused silicon transistor with its thin emitter and base regions provided an ideal test vehicle for this experiment because neutron-induced defects in the base region, when moved less than 0.001 inch from the base to the collector area of the transistor, no longer adversely affected the transistor current gain. All 2N-1051 transistors used in this experiment were previously damaged by neutron bombardment.

32. Kulp, B. A., Jones, J. P. and Vetter, A. F.
Electron radiation damage in unipolar
transistor devices. PROC. INST. RADIO
ENGRS. 49(9):1437-8, Sep 1961.

Degradation of the electrical characteristics of Si and Ga As devices following 1 Me V electron irradiation is reported. The extent of recovery following annealing at temperatures up to 300°C is also noted.

33. Maguire, T.
Production-line diodes being irradiated.
ELECTRONICS 34(4):29, 17 Feb 1961.

Switching diodes are fabricated by conventional methods, but without regard to switching properties. The devices are irradiated and the switching time for the irradiated device of 10 microseconds is cut to 10 millimicroseconds after irradiation with monoenergetic electrons.

34. Miles, T. J. and Watson, G. F.
NUCLEAR RADIATION RESISTANT
POWER TRANSISTORS. Philco Corporation,
Lansdale Tube Co. Division, Lansdale,
Pennsylvania. Second quarterly progress
rept., 15 Aug-15 Nov 1959. Rept. no.
R109-B.

During the period covered by this report, the calibration of the Massachusetts Institute of Technology nuclear reactor was verified. It was demonstrated that exposure of surface barrier transistors in core tube 3GV6 at a power level of 1 megawatt, for periods of 1.8 minutes and 18 minutes will provide accumulated dosages of 10^{13} and 10^{14} nvt, respectively.

35. Nibler, F.
The effects of neutrons on transistors,
especially Ge transistors. ZEITSCHRIFT
FÜR ANGEWANDTE PHYSIK
14(7):394-398, Jul 1962. (In German)

No permanent damage (or practically none) up to doses of about 10^{10} neutrons/cm². With doses in excess of 10^{14} neutrons/cm², all the transistors become nonfunctioning. Although the critical doses in each case are different, the behavior of Nf and Hf on the pnp and the npn transistors agree.

36. Owens, A. R.
THE BEHAVIOUR OF SEMICONDUCTOR
DIODES IN PULSE APPLICATIONS.
United Kingdom Atomic Energy Authority.
Research Group. Atomic Energy Research
Establishment, Harwell, Berks, England.
Rept. no. AERE-M-983, Jan 1962, 25p.

The d-c characteristics of semiconductor diodes are reviewed, and the effects of high-frequency a-c or high-speed pulse inputs on these characteristics are studied. The a-c parameters studied include charge storage, conductivity modulation, and capacitance. These parameters are tabulated for several Ge gold-bonded, junction, and point diodes and Si diodes.

37. Phillips, D. L.
A STUDY OF THE DYNAMIC CHARACTERISTICS
OF THE TUNNEL DIODE AS AFFECTED BY
ELECTRON BOMBARDMENT. Thesis presented
to the Faculty of the School of Engineering of the
Air Force Institute of Technology, Air University,
Wright-Patterson AFB, Ohio. Rept. no.
GE/EE/60-12, Aug 1960. ASTIA AD-246 473.

An audio oscillator using a tunnel diode as the negative resistance element is developed with circuit features that allow the measurement of the dynamic negative resistance of the diode. The tunnel diode was bombarded by 1 Mev electrons, and

simultaneously the diode negative resistance was measured as a function of bias voltage. The negative resistance increased under the electron bombardment and returned almost to its original value when the bombardment was stopped. Total electron dosage on the order of 10^{18} electrons destroyed the negative resistance region of the diode. The possibility of partial recovery of the negative resistance by temperature annealing is indicated.

38. Puttcamp, R.
 NUCLEAR RADIATION DAMAGE TO
 TRANSISTORS. VOLUME I, PERMANENT
 DAMAGE. PART 1, DATA. Diamond
 Ordnance Fuze Labs., Washington, D. C.
 DOFL rept. no. TR-975, 27 Nov 1961,
 161p. (Proj. 23300). ASTIA AD-270 264.

Permanent damage data (including graphical and tabular results) are presented on 18 types of transistors, for design-engineering purposes. Germanium and silicon (PNP and NPN) junction transistors and the 2N128 germanium surface-barrier type are covered. The units were irradiated in a fast neutron environment, produced by a pulsing-type reactor, and observed for effects on small-signal beta and collector leakage current. The results indicate that the amount of induced permanent damage is directly proportional to the power rating of the transistor, and inversely proportional to the alpha-cutoff frequency.

39. Radiation Effects Information Center,
 Battelle Memorial Institute, Columbus,
 Ohio. RADIATION EFFECTS STATE OF
 THE ART, 1961-1962. Rept. to Air Force
 Systems Command, Aeronautical Systems
 Division. REIC rept. no. 24, 30 Jun 1962.
 86p.

Electronic components and equipment; semiconductor devices and materials; polymeric materials; fuels, lubricants and hydraulic fluids; structural metals and alloys; ceramics; space environment; dosimetry; references.

40. Redmond, R. F.
**SPACE RADIATION AND ITS EFFECT ON
 MATERIALS.** Radiation Effects Information
 Center, Battelle Memorial Institute, Columbus,
 Ohio. REIC memo no. 21, 30 Jun 1961, 34p.

Theories concerning the Van Allen belts, cosmic radiation (galactic and solar cosmic rays), interactions of space radiations with matter (electrons, bremsstrahlung, and protons), and radiation, in particular as it affects man and semiconducting devices, are reported.

41. Reid, F. J.
**THE EFFECT OF NUCLEAR RADIATION ON
 SEMICONDUCTOR DEVICES.** Radiation
 Effects Information Center, Battelle Memorial
 Institute. REIC rept no. 10, 30 Apr 1960, 35p.

Information is summarized on permanent radiation effects observed for various silicon and germanium transistors, diodes, and rectifiers. What information is available is presented on infrared detectors, photovoltaic devices, thermoelectric devices, tunnel diodes, SiC rectifiers, and GaAs Zener reference elements.

42. Purdue University, Purdue Research Foundation,
 Dept. of Physics, Lafayette, Indiana. SEMI-
 CONDUCTOR RESEARCH. Quarterly rept. no. 6,
 1 Jan-31 Mar 1962. 31 Mar 1962, 29p. (Contract
 DA-36-039-sc-87394). ASTIA AD-273 975.

Contents include sections on low temperature research; electrical and optical properties, including recombination radiation in GaSb; irradiation effects (optical behavior of irradiated Si, and electron paramagnetic resonance studies for Ge and Si).

43. Sharpless, W. M.
Gallium-arsenide point-contact diodes.
IRE TRANS. MTT-9:6-10, Jan 1961.

The properties of gallium arsenide as a material for point-contact diodes are considered. By controlling the resistivity of the gallium arsenide and the point-contact processing techniques, diodes have been fabricated specifically for use as millimeter wave first detectors, high-speed switches, and reactive elements for microwave parametric oscillators and amplifiers. The operating characteristics of several different types of gallium-arsenide reactive diodes are discussed and simple design formulas which may be used to tentatively evaluate the performance to be expected from such diodes are mentioned. Noise figure measurements are included in a resume covering some of the experimental results that have been obtained using gallium-arsenide point-contact diodes as variable reactance elements in microwave parametric amplifiers.

44. Talbert, A. J. and Wilkin, N. D.
PULSED GAMMA INITIATION OF BREAKDOWN
IN GAS TUBES. Diamond Ordnance Fuze Labs.,
Washington, D. C. Technical rept. no.
DOFL-TR-961, 10 Jul 1961, 21p. (Contract
DA-507-06-011). ASTIA AD-261 821.

Miniature cold-cathode diodes of the GE XD series were subjected to pulses of gamma radiation from the electron linear-acceleration (linac) facility at General Atomic at LaJolla, California, to determine under laboratory conditions the values of gamma dose and dose rate required to initiate breakdown in the diodes at different bias-voltages. Elapsed time between gamma pulse onset and diode breakdown was measured. Curves are presented of the relationship between gamma dose and diode breakdown as a function of diode voltage. The data are compared with similar data taken in Operation Plumbbob (Nevada 1957). The results show that each of the diodes tested is applicable to nuclear-proofing devices with corresponding operating voltage range.

45. Taylor, L.
 Reactor irradiation of semiconductor devices. In PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON AEROSPACE NUCLEAR PROPULSION. Las Vegas, Nevada, 23-27 Oct 1961; IRE TRANS. ON NUCLEAR SCIENCE, NS-9:280-295, Jan 1962.

Some parameter changes of several types of semiconductor devices exposed to a reactor radiation environment were surveyed. Twelve irradiated and eight control specimens from production stock of two diodes and eleven transistor types constituted the experimental groups. The experimental region of the reactor was initially flux mapped, and a flux determination was made for each irradiation. The total dose was about 10^{14} fast neutrons/cm² and 10^8 ergs/gm(c) of gamma rays. Measurement of electrical parameters before, during, and after irradiation indicated a tolerance limit for some devices. The most radiation-resistant transistors measured were silicon double-diffused mesa units types 2N702 and 2N726, and germanium diffused-base mesa units types 2N710 and 2N797. Voltage regulator and switching diodes were hardly affected. Radiation tolerance was greater in the devices with a narrow base region. The increase in tolerable does with increasing gainband-width product is less for germanium than for silicon. There appears to be only a small difference between silicon and germanium in allowable dose for very-high-frequency devices.

46. Taylor, L.
 REACTOR IRRADIATION OF DEVICES .
 Texas Instruments, Inc., Semiconductor-Components Division, Research and Engineering Department. Technical rept., 29 Dec 1960.

By contract, Battelle Memorial Institute performed radiation damage measurements on the following: 2N726, 2N702, 2N697, 2N656, 2N1154, 2N797, 2N710, SCD-015, SCD-033, and SCD-083. The total dose was about 10^{14} fast neutrons/cm² and 10^8 ergs/gm (C) of gamma rays.

Measurement of electrical parameters before, during and after irradiation indicated a tolerance limit for some devices. The most radiation-resistant transistors measured were silicon double-diffused mesa units types 2N702 and 2N726, and germanium diffused-based mesa units types 2N710 and 2N797. Voltage-regulator and switching diodes were hardly affected. Radiation tolerance was greater in the devices with a narrow base region.

47. Tempo Instrument Incorporated,
Plainview, L. I., N. Y. OPERATION
OF TRANSISTOR CIRCUITS IN
NUCLEAR RADIATION FIELDS. Eng.
rept. no. TI-ER-162, 23p.

This report attempts to establish from published reports a so-called "safe" limit of neutron radiation in which transistors and other semiconductors can safely operate. It becomes evident during the discussion that circuit design in addition to choice of specific devices can play a very important role in minimizing radiation effects on the performance of integrated circuits.

48. Tortoriello, P. N.
BEHAVIOR OF GALLIUM PHOSPHIDE
DIODES UNDER FAST-NEUTRON BOMBARDMENT:
APPENDIX F. Bell Telephone Laboratories,
Inc. Sixth triannual technical note, 1 Nov 1960-
15 Mar 1961. Rept. no. ASD-TN-61-81.
15 Mar 1961, p. 135-150.

An investigation of the behavior of gallium phosphide diodes, after exposure to high-energy neutrons (E 0.1 Mev), has been conducted in the swimming pool reactor at the Pennsylvania State University. The experiment consisted of two separate irradiations. Two diodes, irradiated in the first experiment were Westinghouse experimental gallium phosphide rectifiers. These units were exposed to a total integrated fast-neutron flux of 1.05×10^{16} neutrons per cm^2 . The second experiment used two BTL diodes which were exposed to a total integrated fast-neutron flux of about 4.57×10^{15} neutrons per cm^2 . Each experiment consisted of a number of successive exposures at various reactor power levels. Data concerning the effects of this environment on the voltage-current characteristics after each exposure and a description of the experimental procedure are given.

49. Tortoriello, P. N.
 BEHAVIOR OF ZINC-DIFFUSED GALLIUM
 PHOSPHIDE DIODES UNDER FAST-NEUTRON
 BOMBARDMENT: APPENDIX E. Bell
 Telephone Laboratories. Fifth triannual
 technical note, 1 Jul-31 Oct 1960. Rept.
 no. WADD-TN-61-17, 15 Nov 1960, p. 65-72.
 (Contract AF 33(616)6235).

The results of this experiment indicate that the GaP diodes examined exhibited little or no change in the forward or reverse $V_C - I_C$ characteristics when exposed to integrated fast-neutron fluxes of the order of 1.77×10^{13} n/cm². The junctions that were available to us at this time were among the first of their kind. Improved versions with alloyed contacts have been fabricated. Upon the availability of these units, further studies of their electrical characteristics, including junction capacitance, will be conducted at much higher neutron fluxes.

50. Vaughan, D. E.
 Low dose gamma irradiation of semiconductor
 diodes. J. ELECTRONICS AND CONTROL.
 1(12):233-41, Mar 1962.

Investigations were made of the effects of small (10 kilorad) doses of Co⁶⁰ gamma radiation on p-n junction germanium diodes, with particular reference to changes in reverse saturation current and junction depletion capacitance under reverse bias conditions. Significant post-irradiation changes were observed in both parameters and a mechanism is proposed to explain the major features of the observations.

51. Vaughan, D. E.
 Low dose gamma irradiation of alloy junction
 transistors. JOURNAL OF ELECTRICS AND
 CONTROL (GREAT BRITAIN)
 12(4):307-312, Apr 1962.

Ten kilorad doses of Co⁶⁰ gamma radiation on pnp alloy junction transistors, with particular reference to effect upon gain and minority carrier lifetime.

52. Westmark, C. I.
**RADIATION TOLERANCE OF A SELECT
 GROUP OF SEMICONDUCTOR DEVICES.**
 Sandia Corp. , Albuquerque, New Mexico.
 Rept. no. SCTM-404-60-(14), 23 Nov 1960.

A select group of reference-type silicon diodes were irradiated through an integrated flux range from 10^{13} nvt to 7×10^{16} nvt ($E > \text{kev}$). Parameters that would indicate displacement damage were monitored during the irradiation. This report gives a brief presentation which shows the qualitative nature of findings, and recommendations are made on how quantitative results could be obtained in the future.

53. Yamaguchi, K.
 Deterioration of germanium phototransistors
 due to gamma-irradiation. OYO BUTSURI,
 31(5):367-68 (1962).

54. Zagorites, H. A. , Carr, E. A. and Durkee, J.W.
**TRANSIENT EFFECTS IN MILITARY ELECTRONIC
 EQUIPMENT EXPOSED TO NUCLEAR FALLOUT.**
 U. S. Naval Radiological Defense Laboratory,
 San Francisco, California.

A group of 30 2N522A Ge transistors, 2N479A Si transistor, IN55B and 1N100, Ge diodes and 1N663 and 1N643 Si diodes were irradiated at 10^6 r/hr for 30 minutes. The collector-to-base current, Beta, and reverse diode current were measured.

55.

Zander, K.

Measurements of the radiation resistance of
transistors. NUKLEONIK

3(7): 292-5, Dec 1961. (In German)

Current gain, leakage current, output impedance and other parameters were observed on Si and Ge alloy transistors and on Ge alloy-diffused and Ge mesa transistors during irradiation in the research reactor BER. Reciprocal of the current gain with common emitter increased nearly linearly with the fast neutron dosage but increased at about 1/10 the rate for Ge-alloyed to that for Si-alloyed units of similar cutoff frequency (~ 4 Mc/s), though the rate is reduced by a further factor of 10 for a Ge mesa structure of about 300 Mc/s cutoff frequency. It was found that the leakage currents increase and the output slope resistances decrease with increased dosage, at high rates for low-frequency Ge-alloyed transistors but more slowly for h.f. types.

Part II

RADIATION EFFECTS ON SEMICONDUCTING MATERIALS:
GERMANIUM; SILICON; COMPOUND SEMICONDUCTING MATERIALS
(EXCLUSIVE OF ALKALI HALIDES)

A - Radiation Effects on Semiconducting Materials: Combined Treatment

56. Ammons, J. W.
ABSORPTION EDGE SHIFT MEASUREMENTS
OF GERMANIUM AFTER BOMBARDMENT
BY 1-MEV ELECTRONS: APPENDIX B.
Bell Telephone Laboratories, Inc.
Sixth triannual technical note, 1 Nov 1960-
28 Feb 1961. Rept. no. ASD-61-81,
15 Mar 1961, p. 25-34.

Effects produced by 1-Mev electron bombardment and by bombardment with heavy particles have been observed. The optical band edge of the semiconductor occurs at the wave length at which photons no longer can induce band-to-band transitions.

57. Anderson, G. S. and Wehner, G. K.
Atom ejection patterns in single-crystal
sputtering. J. APPL. PHYS.
31:2305-2313, Dec 1960.

Experimental studies of the atom ejection patterns in single-crystal sputtering, mostly by Hg⁺ ions, are discussed. These patterns give evidence of the anisotropic spread of energy from a collision center, and support the concept of focusing collisions in nearest and next-nearest neighbor directions. In Ge the patterns were found to be strikingly similar to those from a bcc crystal. This could be explained by assuming that under ion bombardment so many interstitials are formed near the surface that the atom arrangement of the Ge crystal resembles that of a bcc lattice.

58. Aukerman, L. W., Davis, P. W. and
Shilliday, T. S.
Optical absorption of neutron-irradiated
semiconductors. BULL. AM. PHYS.
SOC., Ser II 7:51(A), 24 Jan. 1962.

Measurements of the optical absorption at wavelengths beyond the fundamental absorption edge of GaAs, CdS, and CdTe irradiated by fast neutrons were reported. Fluxes in the range of 10^{16} to 4×10^{17} neutrons/cm² were employed. The radiation-induced optical absorption decreases smoothly with decreasing proton energy. In the case of GaAs and CdTe the absorption coefficients increase approximately as the square of the proton energy in the region between the band edge and about 1 ev below it. This radiation-induced absorption may arise from the inhomogeneous nature of the fast-neutron damage. Light scattering may play an important role. The likelihood that minute regions have been converted to a different phase by the fast neutron encounters is an attractive hypothesis since all three of the materials have been shown to undergo irreversible phase transformations after they have been subjected to very high pressures. Microscopic strains may shift the band edges to lower energies. The observed shift of the band edge in Si might be explained by a similar mechanism if highly strained regions are present, since high pressure decreases the band gap in Si.

59. Aukerman, L. W. and Graft, R. D.
Some radiation effects on GaAs.
In SYMPOSIUM ON EFFECTS OF SPACE
ENVIRONMENT ON MATERIALS, SOCIETY
OF AEROSPACE MATERIAL AND PROCESS
ENGINEERS. St. Louis, Missouri,
7-9 May 1962, 25p. St. Louis, published
courtesy of McDonnell Aircraft Corporation,
1962.

60. Baruch, P., et al.
Vacancy-enhanced diffusion in silicon.
Effects of irradiation and of chemical
impurities. DISCUSSIONS FARADAY
SOCIETY (31):76-85 (1961).

A p-n junction, obtained by Ga diffusion, increases in depth as result of proton bombardment, indicating that the Ga has diffused into the crystal faster than in the nonirradiated region. Possible explanation: introduction of donors increases local vacancy concentration by ionizing interaction, the vacancies enhancing the acceptor diffusion rate.

61. Bauer, C. L. and Gordon, R. B.
Structure sensitivity of F-center
generation by x-rays at low temperatures.
PHYS. REV. 126:73-8 (1962).

Temperature-sensitivity of F-center formation, for crystals only lightly deformed by irradiation and for those more heavily deformed.

62. Binder, D.
Effect of fission spectrum neutrons on n-type
germanium. PHYSICAL REVIEW
122:1147-1148, 15 May 1961.

It is reported that the electron removal rate for n-type germanium irradiated with fission spectrum neutrons is 8 ± 1 per neutron at room temperature. This value is compared with the results of monoenergetic neutron irradiations from 2 to 5 Mev. The fact that the removal rate is roughly constant is explained by the constancy of the energy dissipated in elastic collisions.

63. Semiconductors dominated by impurity levels.
In Blakemore, J. S. SEMICONDUCTOR
STATISTICS. Chap. 3, p. 164-166. New York,
Pergamon Press, 1962. 381p. (International
Series of Monographs on Semiconductors, Vol 3)

64. Brown, W. L.
**SEMICONDUCTOR RADIATION DAMAGE
 IN SPACE: APPENDIX A.** Bell Telephone
 Laboratories, Inc., New York, N. Y.
 Triannual technical note, 1 Mar-30 Jun
 1961. Rept. no. ASD-TN-61-137,
 15 Jul 1961, p. 13-23. (Contract
 AF 33(616)6235).

The material is concerned with permanent or semipermanent integrated radiation damage effects in semiconductors. It is involved chiefly with effects due to electrons and protons because of recent interest in these particles and their influence on communication satellite systems in the region of space containing the Van Allen belts.

65. Cleland, J. W. and Crawford, Jr., J. H.
 Radiation-induced disorder in semiconductors.
In PROCEEDINGS OF THE INTERNATIONAL
 CONFERENCE ON SEMICONDUCTOR PHYSICS,
 PRAGUE, 1960. New York, Academic Press
 and Prague Publishing House of the Czechoslovak
 Academy of Sciences, 1961. 1133p.

The variation of σ and u_H of n-type germanium with neutron bombardment was treated on the basis of a disordered region model of lattice damage. It is found that the bulk of the initial changes in these properties can be accounted for in terms of disordered regions $\sim A$ in radius for the neutron spectrum employed.

66. Closser, W. H.
Drift mobility in neutron irradiated n-type germanium. JOURNAL OF APPLIED PHYSICS 31(9):1963, Sep 1960.

Measurements of drift mobility in neutron irradiated n-type germanium indicate an initial increase in the drift mobility for low values of flux, prior to the decrease which normally occurs as the material approaches intrinsic, resulting from the radiation.

Neutrons were obtained from a Van de Graaff accelerator and the Omega West reactor facility at Los Alamos.

67. Cole, R. L.
DEVELOPMENT OF SILICON INFRARED OPTICAL COMPONENTS. Texas Instruments, Inc., Materials & Sensors Dept., Semiconductor Components Division. Quarterly progress rept. no. 6, 1 Mar-1 Jun 1960. (Contract AF 33(600)38085).

The effect of irradiation on the absorption coefficient of low resistivity n-type single crystal silicon was determined. 11.4 mm thick specimens were exposed to 5×10^{15} n/cm² in an oxygen atmosphere and in a vacuum at 100 C.

68. Corbett, J. W., Watkins, G. D. and Chrenko, R. M.
Infrared studies of electron irradiated silicon 1. BULL. AM. PHYS. SOC., Ser. II 5:25-26(A), 27 Jan 1960.

The IR absorption spectrum (1.4-14 μ) of silicon irradiated at room temperature with 1.5 mev electrons was discussed. A sharp band at 12 μ with an intensity roughly proportional to the concentration of dissolved oxygen originally in the silicon has been observed. The production rate of this band vs. irradiation correlates with that of the defect previously studied in spin resonance (A center) and in electrical measurements (net acceptor at E -0.17 ev), which has been shown to be strongly dependent upon oxygen content. The annealing behavior of the 12 μ band is similar to

that of the other measurements, again suggesting that they arise from the same defect. In a sample enriched with 14 percent O^{18} , a small subsidiary peak is observed which identifies the 12μ absorption as arising from the vibration of a single oxygen atom. These data lend support to the model proposed from spin resonance studies that the A center, which is the dominant defect produced by irradiation in pulled silicon, involves an oxygen atom trapped in a lattice vacancy.

69. Corbett, J. W. and Watkins, G. D.
Silicon divacancy and its direct production
by electron irradiation. PHYSICAL
REVIEW LETTERS 7:314-316 (L),
15 Oct 1961.

The divacancy, an intrinsic defect which is stable at room temperature and which is produced by room temperature electron irradiation of Si, is discussed. The divacancy is produced directly in a high energy electron irradiation. The high anisotropy of the divacancy production rate indicates that the divacancy is produced by the following process: A high energy electron collides with the nucleus of an atom and imparts a recoil energy to the atom, causing it to be displaced into the lattice as an interstitial. The initial recoil atom retains enough energy so that it also becomes an interstitial. The divacancy production rate is ~ 5 per cent of the vacancy production rate of 1.5 Mev irradiation and plays an important part in room temperature radiation damage processes.

70. Corbett, J. W., et al.
Defects in irradiated silicon. II. Infrared
absorption of the Si-A center. PHYSICAL
REVIEW 121:1015-1022, 15 Feb 1961.

Infrared measurements (in conjunction with previously reported spin resonance measurements) establish the identity of the radiation damage defect known as the Si-A center. A new infrared absorption band has been observed at 12μ in electron-irradiated silicon. This band is shown to be a vibrational band of impurity oxygen in the lattice. Macroscopic and microscopic correlations between the 12μ band and the spin resonance of the Se-A center are presented. The macroscopic correlations are of production rate, recovery, etc. The microscopic correlations derive from the absorption of polarized infrared radiation by samples of various crystallographic orientations, subjected to a uniaxial, compressive stress. Partial alignment of the

defects is induced by the stress and is detected as a dichroism in the 12- μ band. The alignment is compared to the corresponding alignment studies in spin resonance measurements. It is shown that the kinetics and magnitude of the response to the stress are the same for the defects observed in both types of measurements. This shows that the 12- μ band arises from the Si-A center and established the configuration of the oxygen in the defect. These results indicate that the Si-A center is a lattice vacancy with an oxygen atom bridging two of the four broken bonds associated with the vacancy. The remaining two bands can trap an electron, giving rise to the spin resonance spectrum of the defect. The identification of the Si-A center indicates that the vacancy is mobile in a room temperature irradiation.

71. Dillon, J. A., Jr. and Oman, R. M.
Ion-bombardment etching of silicon and
germanium. JOURNAL OF APPLIED PHYSICS
31:26-28, Jan 1960.

Ion-bombardment-induced etch pits on silicon and germanium surfaces are discussed. Electron-microscope photographs of a germanium single crystal surface subjected to prolonged argon ion bombardment under conditions used for surface cleaning disclosed etch patterns of a type completely different from those observed after chemical etching alone. The dimensions and distribution of the bombardment-induced pits were such that the patterns were not detectable either with an optical microscope or by low-energy electron diffraction. Approximately 95 percent of the surface remained undamaged. Bombardment of silicon and germanium at 500 ev for prolonged periods at higher current densities produced a different type of etching which may be associated with screw-type dislocations.

72. Fan, H. Y. and Ramdas, A. K.
Infrared absorption in irradiated silicon.
In PROCEEDINGS OF THE INTERNATIONAL
CONFERENCE ON SEMICONDUCTOR PHYSICS,
PRAGUE, 1960, p.309-312. New York, Academic
Press, and Prague, Publishing House of the
Czechoslovak Academy of Sciences, 1961, 1133p.
(In English).

Two types of absorption bands produced in silicon by neutron or electron bombardment are discussed: the 1.8 μ band and a number of bands in the 9 to 14 μ region. Most of the bands in the latter group depend on the presence of dispersed oxygen. The 1.8 μ band is produced by neutron irradiation irrespective of impurities in the sample. The center has an axis along (110) directions, probably due to vacancy or interstitial pairs.

73. Gartner, W. W., Mette, H., and Lascoe, C.
 Photothermal (PT) effect in semiconductors.
 BULL. AM. PHYS. SOC., SER. II.
 6:28(A), 1 Feb 1961.

When a sample of semiconducting material is illuminated with photons of sufficient energy, electron-hole pairs are generated which diffuse through the crystal from the place of their generation to regions of lower excess-pair concentration. Each pair transports an amount of energy approximately equal to the band separation, thus contributing to the thermal conductivity. This energy is deposited where the pair undergoes nonradiative recombination, increasing the local (measurable) temperature of the crystal. A nonuniform temperature distribution is therefore established in the sample which depends on the nature of the incident radiation, on the characteristics of optical absorption, on the bulk and surface recombination mechanisms, on the boundary conditions for temperature and energy flux and on the ordinary thermal conductivity of the material. This establishment of a temperature distribution in a solid by optically excited diffusing and recombining carriers and the attendant modification in the thermal conductivity is called the Photothermal (PT) Effect. It is the thermal analog to the December effect. Its deflection by a magnetic field is called the Photomagnetothermal (PMT) Effect. A simple theory of the PT effect which appears applicable to germanium and silicon was presented and experimental problems were discussed.

74. Gorkun, Yu. I.
 The field effect theory. UKRAIN. FIZ.
 ZHUR. 6:567-70, Jul-Aug 1961.
 (In Ukrainian)

A field effect theory was developed for semiconductors by referring to imperfect ionization of impurity centers, both donors and acceptors. This theory may be applicable for measuring the field effect at liquid nitrogen temperatures although express temperature limitations have been imposed. However, scattering of the volume charge causes complications. Therefore, in order to extend the applicability of the theory and to form a universally valid theory of the ionization of impurities, the energy relationships of the localized points must be better known.

75. Harburn, G. W., Kitchingman, W. J., and
Edmunds, I. G.
Conference on Imperfections in crystals,
London, Nov 1961. BRITISH JOURNAL OF
APPLIED PHYSICS 13(6):253-256, Jun 1962.

Brief review of papers presented. Vacancy formation due to irradiation and other means was discussed by several of the speakers.

76. Hobstetter, J. N., and Renton, C. A.
Point defects in p-type germanium as introduced
by deformation, quenching, and electron
bombardment. JOURNAL OF APPLIED
PHYSICS 33:600-605, Feb 1962.

Starting with the same material, 5 ohm-cm p-type germanium, Hall measurements were made after different treatments, in order to compare point defect formation in germanium through different means for producing these defects. Interpretation of results attempts to find logical basis of explanation for the disparate results observed, namely that (1) quenching introduces a constant number of new holes; (2) that deformation leads to annealable cross-over effect where holes are increased at high temperatures and decreased at low temperatures; (3) studies of the damage centers introduced by electron bombardment show that bombardment causes the number of holes to decrease at all temperatures with the greater effect at lower temperatures.

77. H. Heinrich
Modifications of silicon under intense bombard-
ment with 50 to 100-keV electrons. Z. ANGEW
PHYS. 14:9-12, Jan 1962. (In German)

n-conducting Si with a specific electrical resistance of $11 \Omega \text{ cm}$ was irradiated for a short time with intense electron beams. 50-keV electrons at $10^{14} \text{ electrons/cm}^2$ gave no modifications, but $9 \times 10^{16} \text{ electrons/cm}^2$ induced conversion from n to p conducting material on the basis of measured rectifying characteristics. 100-keV electrons at a rate of $4 \times 10^{17} \text{ electrons/cm}^2$, which heat the material to a great degree, erases this conversion. Under extended irradiation at equal irradiation rates, the n-p conversion first proceeds at a faster rate and is thermally quenched at a higher rate in comparison with short-time irradiation. The conversion can be traced back to Frenkel defects for which unexpected low production energy of less than 4 eV/defect suggested a surface mechanism, in contrast to the higher energy necessary for the volume mechanism.

78. Hora, H.
Variation of the absorption of silicon evaporated
layers after bombardment with 75 kev electrons.
NATURWISSENSCHAFTEN (GERMANY)
48(20):641 (1961). (In German)

Evaporated layers were 2 to 5μ thick, and made with p-type silicon of 10^4 ohm cm resistivity. An almost parallel displacement (0.15–0.2 eV) of the whole absorption curve towards shorter wavelengths was observed after bombardment with 3×10^{16} electrons/cm². The effect was felt to be due to some change in the whole structure of the layer, since the displacement of the edge indicates that the band gap has increased from 1.3 to 1.5 eV.

79. Kokorish, E. , Yu. , and Sheftal, N. N.
Dislocations in semiconductor crystals.
USPEKHI FIZ. NAUK (USSR) 72(3):479–94,
Nov 1960. (In Russian)

A general review of work done in the U.S.A. , the United Kingdom, U.S.S.R. , and France, up to 1959. (English translation in: Soviet Physics – Uspekhi (U.S.A.), Vol 3, No. 6, 840–849 (May–June 1961).

80. Meckel, B. B. , Schwarz, E. G. K. and
Swalin, R. A. Microscopic study of
neutron-irradiated germanium. JOURNAL
OF APPLIED PHYSICS 31(7):1299, Jul 1960.

A microscopic study of germanium irradiated at 10^{10} and 10^{13} nvt is reported. Etching revealed numerous small etch pits of random distribution in the exposed specimens; the strange pattern being superimposed on the background of the blank which is due to the screw-component dislocations ordinarily present in Ge crystals. The etching behavior of the strange pattern indicates the presence of highly strained, well-defined regions of structural damage.

81. Miller, Yu. G.
Investigation of electrical transport in metals
and semiconductors under the influence of the
Hall electric field. FIZIKA TVERDOGO TELA
3(8):2383-2389, Aug 1961. (In Russian)
English translation in Soviet Physics - Solid
State, p. 1728-1732, Feb 1962.

A new method of ion-charge determination, based on investigations of electrical transport of ions in a Hall transverse electric field.

82. Naber, J. A., and James, H. J.
Effect of hydrogen on the displacement process
in Ge. BULLETIN AMERICAN PHYSICAL
SOCIETY, SERIES II 6:303 (A), 24 Apr 1961.

Hypothesis for the low-energy irradiation effects in Ge, (in which the electron bombardment displacement threshold is less than 360 kev) the hypothesis evolving upon the concentration of hydrogen atoms in Ge crystals. It was stated that these "below threshold" effects might be due to displacement of Ge atoms resulting from a two-step process in which the electron initially strikes a hydrogen atom which then collides with a lattice atom. The maximum energy transferred to the Ge atom in the two-step process is four times that for a direct electron-Ge collision; thus the threshold for producing a displacement by the two-step process should be about 100 kev. An order of magnitude calculation indicates that in the presence of 10^{18} hydrogen atoms/cm³ there will be about 10^{-6} displaced Ge atoms/cm/incident electron at 300 kev. Comparison of irradiations of crystals grown in a hydrogen atmosphere with crystals grown in a vacuum shows that hydrogen-grown crystals have conductivity changes consistent with the above calculations, while vacuum-grown crystals are essentially unaffected by "below threshold" irradiation. The results suggest that the two-step hypothesis is a likely explanation of the low-energy irradiation effects in Ge.

83. Nazarewicz, B. W.
INDIRECT ABSORPTION EDGE IN GERMANIUM
BOMBARDED BY FAST NEUTRONS. Polish
Academy of Sciences, Institute of Nuclear
Research. AEC. Rept. no. NP-8661, 1959.

This paper reports the results of absorption measurements for germanium single crystals with various concentrations of structural defects introduced by fast neutron bombardment. It was found that the edge is of the form expected for indirect transitions accompanied by phonon interaction. An analysis of absorption data on the basis of the Macfarlane-Roberts formula yield values for the indirect energy gap and the temperature of the phonon involved. Various concentrations of defects were obtained by partially annealing at various elevated temperatures.

84. PROCEEDINGS OF THE INTERNATIONAL
CONFERENCE ON SEMICONDUCTOR PHYSICS,
PRAGUE, 1960. New York, Academic Press
and Prague, Publishing House of the
Czechoslovak Academy of Sciences, 1961.
1133p.

Two hundred and seventy papers are included. 188 papers are in English, 37 in Russian, 24 in German, and 20 in French. The information is devoted to the fundamental problems in the physics of semiconductors, both from the experimental and theoretical points of view. Information is given on band structure and related problems, transport phenomena, recombination, radiation damage, optical properties, optical and magneto-optical effects, photoconductivity, surface phenomena, resonance, thermal properties and thermoelectricity, ionic crystals, and semiconductor materials.

85. Ramasastry, C.
Energy states associated with crystal defects
in semiconductors. In SYMPOSIUM ON
SPECTROSCOPY. R. K. Asundi, editor.
Muzaffarpur: University of Bihar, Bombay,
India. 2 Jan 1960, p. 128 - 139.

For germanium and silicon, energy levels are shown, taking into account extrinsic defects and radiation damage.

86. Sadagopan, V.
A review of experimental techniques used
in the study of crystal imperfections.
SOLID STATE ABSTRACTS 3(1):9-18.

Reviewed in this beginning series are nuclear magnetic resonances; internal friction; neutron and electron diffraction. X-ray and other experimental techniques will be reviewed in later issues. References are cited in this evaluation of findings on the nature, concentration and interaction of defects in semiconductors (bulk matter and crystals). Radiation effects given only incidental treatment.

87. Sirotenko, I. G., and Spivak, G. V.
Detection of edge dislocations in germanium
by ionic bombardment. KRISTALLOGRAFIYA
(USSR) 6(2):274-7, Mar-Apr 1961. (In Russian)

Method for detecting in germanium crystals both small angle tilt boundaries and isolated edge dislocations, the method based on the bombardment of the specimen by accelerated heavy ions (cathode sputtering). English translation in: Soviet Physics - Crystallography (USA), Vol. 6, No. 2, 213-15 (Sep-Oct 1961).

88. Smirnov, L. S.
Radiation defects in crystals. SOVIET
PHYS. - SOLID STATE 2:1512-1513, Jan 1961.

The formation, structure, and restoration of radiation defects in crystals is discussed. Energy of impact is transferred from the primary excited atom to other atoms nearby, permitting their movement due to localized melting. A defect is established if order is not restored in the melted region upon its hardening. The possibility of such an occurrence in silicon and germanium is theorized. In germanium, an approximate calculation indicates that 26 atoms will be contained in the minimum volume of the localized melted region in which reordering is possible, upon subsequent thermal oscillations.

89. Van Dong, N.
Effect of nuclear radiations on the electronic properties of semiconductors. BULL. INFORM. SCI. ET TECH. (PARIS) 56:28-38, Nov 1961.
(In French)

The study of damage caused to semiconductors by radiations is reviewed. Two aspects of the problem are approached: the mechanism of the creation of defects in a crystal lattice under the action of bombardment and effects on the electronic properties. The problem of neutron dosimetry in a reactor is also discussed.

90. Vavilov, V. S.
Radiation ionization processes in germanium and silicon crystals. SOVIET PHYSICS USPEKHI 4(5):761-769. (In English) (Trans. from Usp. Fiz. Nauk. 75, 263-276, Oct 1961).

By radiation ionization the author means the production of current carriers due to radiation energy, here limited to those phenomena of photoionization and ionization due to charged particles which result from the liberation of valence electrons in semiconductor crystals.

91. Vitovskii, N. A., et al
The energy spectrum of defects produced by γ -rays in germanium. SOVIET PHYS. - SOLID STATE 3:727-729(L), Sep 1961.

The positions of three of the four acceptor levels of radiation defects in Ge are discussed. The uppermost four levels of a defect should be empty at absolute zero. These layers may be filled by electrons from impurity donors in Ge doped with elements of group V. By altering the concentration of defects it is possible to obtain different ratios of the defect concentration and the impurity donor concentration. The temperature dependence of the Hall constant of samples of all five possible ways of occupation of the uppermost defect levels in the forbidden band have been measured. Results indicate that either all the defect levels are of acceptor type, or some are donor levels with an appropriate number of acceptor levels below ($E_v + 0.02$) ev. Values for the four bands are given.

92.

Vol'kenshtein, F. F.

The effect of ionizing radiation on the
adsorption and catalytic properties of
semiconductors. KINETIKA I KATALIZ
2:481-9, Jul-Aug 1961. (In Russian)

The mechanism of radiation effects on adsorption equilibrium, adsorption kinetics, and the rate of catalytic reaction is analyzed within the limits of the electron theory of chemisorption. An analysis is also made of the radiation effect as functions of temperature, pressure, and the composition of the specimen.

93.

Vook, Frederick L.

Low-temperature length change measurements
of electron-irradiated germanium and silicon.
PHYSICAL REVIEW 125(3):855-861, 1 Feb 1962.

Precision measurements of the change in length of high-purity germanium and silicon were made upon 2 Mev electron irradiation and annealing. Two germanium samples were irradiated at maximum temperatures of 365 K and 86 K, respectively. The first sample was irradiated at $33\mu\text{ a/cm}^2$ to an integrated flux of 5.4×10^{19} electrons/cm². The specific length expansion obtained was $\Delta L/L = (6 \pm 12) \times 10^{-26}$ per 2Mev electrons/cm². The 86 K sample was irradiated at $10\mu\text{ a/cm}^2$ to an integrated flux of 3.0×10^{19} electrons/cm². The specific length expansion was $(1.5 \pm 3.9) \times 10^{-25}$ per 2-Mev electrons/cm². The silicon sample was initially irradiated at $\sim 50\text{ K}$ to an integrated flux of 8.3×10^{18} electrons/cm² and further irradiated at $\sim 115\text{ K}$ to a total integrated flux of 7.9×10^{19} electrons/cm² and then annealed to room temperature. The specific length change for both bombardments was $\Delta L/L = (4 \pm 19) \times 10^{-26}$ per 2 Mev electrons/cm². These values are much smaller than would be expected from previous results for deuteron and neutron irradiations of germanium. Calculations of defect cluster size distributions for electron, deuteron, and neutron irradiations of germanium are given and combined with the experimental results to indicate that the volume change per defect is nonlinear and increases as the cluster size increases. The samples were not observed to expand within the presumed error. All measurements did, however, yield a small positive value. The values for Ge and Si are very small compared with the large expansions recently observed for electron-irradiated InSb and GaAs.

94. Wittels, M. C.
Lattice vacancies in neutron irradiated germanium. BULLETIN OF AMERICAN PHYSICAL SOCIETY, SERIES II 5:375(A), Jun 15, 1960.

Defects produced in 40 ohm-cm p-type Ge single crystals as a result of exposure at approximately 85°C to fast neutron fluxes of up to 4×10^{20} neutrons/cm² are discussed. X-ray diffraction and hydrostatic weighing measurements indicate that at these dosages and temperatures sufficient defects are trapped so that density reductions as high as 5×10^{-3} develop. In addition, a pronounced variation in the densities as determined by unit cell measurements and those obtained from hydrostatic weighing reveals that the predominant defects stable at room temperature are vacancies.

95. Yurkov, Ya.
Theory of the spatial distribution of radiation disturbances of the crystal lattice of silicon when irradiated with a multienergetic electron beam. FIZIKA TVERDOGO TELA 1(5):696, May 1959. (In Russian) English translation in: SOVIET PHYSICS - SOLID STATE 1(5): 633-641, Nov 1959.

The method developed by Spencer for the calculation of the spatial distribution of the energy losses on an electron beam has been applied to the determination of the spatial distribution $\Sigma(x)$ of the radiation disturbances of the crystal lattice of silicon. Radiation losses produced by retardation are not great for the range of electron energy $E \leq 0.5$ Mev [1].

B - Annealing of Radiation Defects

96. Asada, T., et al.
Annealing of γ -ray damage in germanium.
J. PHYS. SOC. JAPAN 15:93-94, Jan 1960.

The isothermal annealing, in the temperature range 10-55° of germanium single crystals irradiated with γ -rays from Co-60 is discussed. The variation of conductance with time was measured and it was found that, at a given annealing temperature, the conductance initially increased, then decreased to a certain value, and finally increased asymptotically to a final value. A modification of the model proposed by Fletcher and Brown may be used to explain these observations. From an analysis of these curves, the activation energies for direct recombination of vacancy-interstitial pairs, for the diffusion of interstitial atoms, and for diffusion of vacancies are found to be 0.765 ev, 0.741 ev, and 1.250 ev, respectively.

97. Asakawa, T.
The effect of heat treatment on the minority-carrier lifetime in silicon. J. PHYS. SOC. JAPAN 16:1923-33 (1961).

Heat treatment centers introduced into silicon were studied by measuring the minority carrier lifetime. The donor-like level at 0.34 e.v. from the valence band seen immediately after quenching was transformed into recombination levels of various types - one located at a distance larger than 0.45 ± 0.05 e.v. Transformation centers with small activation energy could not be explained by the Shockley-Read formula. The thermally introduced center is considered to be Fe, acting as a recombination center even although inactive in terms of electrical conductivity.

98. Aukerman, L. W. , et al.
**THEORETICAL AND EXPERIMENTAL
 STUDIES CONCERNING RADIATION DAMAGE
 IN SELECTED COMPOUND SEMICONDUCTORS.**
 Battelle Memorial Institute, Columbus, Ohio.
 Third interim progress rept. , 15 Aug - 15 Nov
 1961. 15 Nov 1961, 18p. (Contract
 AF 33(616)8064).

Isothermal annealing experiments on neutron-irradiated n-type GaAs have been analyzed in terms of two independent monomolecular processes. Since a similar behavior has been observed in electron-irradiated GaAs, direct comparisons have been made between the two types of damage. Isochronal annealing studies on neutron-irradiated n-type InP indicate that this material may have a more complex defect structure than does GaAs when irradiated at or near room temperature. Optical-transmission data obtained from neutron-irradiated GaAs, CdTe, and CdS are discussed in terms of a model in which the damaged sites consist of localized regions of a different phase.

99. Aukerman, L. W. , Baroody, E. M. , and
 Graft, R. D.
**THEORETICAL AND EXPERIMENTAL
 STUDIES CONCERNING RADIATION DAMAGE
 IN SELECTED COMPOUND SEMICONDUCTORS.**
 Battelle Memorial Institute, Columbus, Ohio.
 Second interim progress rept. , 15 May - 15 Aug
 1961. 15 Aug 1961, 14p. (Contract
 AF 33(616)8064).

The defects introduced in n-type GaAs by irradiation at room temperature with energetic electrons anneal out in a manner which can be described in terms of two first-order processes. The first of these processes appears to be independent of the various extrinsic properties of the many specimens studied. The rate constant for the second process is proportional to the carrier density. This suggests that the mobility of the defects which anneal during the second process is influenced by the position of the Fermi level; consequently, the results are analyzed under this assumption. The annealing of two p-type GaAs specimens after electron irradiation shows three rather distinct stages of annealing. The results from one specimen suggest that first-order annealing kinetics is not obeyed in the p-type samples.

100. Bauerlein, R.
Investigations of the healing process for
frenkel defects in indium arsenide.
Z. NATURFORSCH. (GERMANY)
16a(10):1002-7, Oct 1961. (In German)

For frenkel defects produced in a barrier element of InAs at 65°K by bombardment with 400 keV electrons, the defect concentration is deduced from changes of the short-circuit current of the barrier element. Several characteristic healing steps occur, especially at 85°, 120° and 300°K. At 300°K all lattice defects produced by bombardment are removed. The activation energy for the healing is found to be 0.08 eV.

101. Chapman, C. M., et al.
RESEARCH STUDIES AND INVESTIGATIONS
OF MATERIALS SENSITIVE TO RADIATION
IN THE 8 TO 14-MICRON REGION OF THE
INFRARED SPECTRUM. Battelle Memorial
Institute, Columbus, Ohio. Quarterly progress
rept. no. 8, 1 Jul-30 Sep 1961. 20 Oct 1961,
18p. (Contract DA 44-009-eng-3951).
ASTIA AD-273 204L.

Electrical properties of HgTe-CdTe alloys of high HgTe content are readily affected by annealing at elevated temperatures in Hg vapor. The alloys as prepared are p-type at temperatures well below 77 K. Annealing at 500 C at high Hg vapor pressures changes conductivity to n-type, with an attendant increase in carrier density. P-type material is again produced when further annealing at 500 C is done at low Hg vapor pressures. A wet chemical method of determining the composition of HgTe-CdTe alloys was devised. The response of HgTe-CdTe alloy cells to white light and to monochromatic IR radiation is predominantly thermal.

102. Corelli, J. C., Frost, R. T., and Amorosi, D. M.
 Annealing of reactor radiation damage in lead and bismuth tellurides.
In PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON AEROSPACE NUCLEAR PROPULSION. Las Vegas, Nevada, 23-27 Oct 1961, IRE Transactions on Nuclear Science NS-9(1):303-309, Jan 1962.

Bismuth and lead tellurides of both n- and p-types were irradiated in the Engineering Test Reactor at specimen temperatures of $60 \pm 20^\circ\text{C}$. Electrical resistivity and Seebeck coefficients were measured before and after the irradiation and again during annealing experiments in order to determine the extent of recovery in these properties which could be affected by post-irradiation heat treatments. The thermal neutron flux dose was 6×10^{20} n/cm² with a fast neutron dose of 5×10^{19} n/cm². There was little difference between the results for the cadmium shielded and the unshielded specimens, confirming earlier results that the principal damage is due to fast neutrons. The permanent damage due to transmutation effects was so small as to be unobserved in the presence of the much larger damage from fast neutrons and could be seen only after the fast neutron damage was annealed out. The Hall coefficients as a function of inverse temperature after annealing were very close to results obtained for unirradiated material. The increase in Seebeck coefficients for the irradiated specimens were found to be about 30% less than the change which would be expected from the change in carrier concentration alone. The Seebeck coefficients in the irradiated specimens after annealing were comparable to those in unirradiated specimens.

103. Corelli, J. C., and Amorosi, D. M.
 CHARACTERISTICS AND ANNEALING OF NEUTRON-IRRADIATED PbTe.
 Knolls Atomic Power Lab., Schenectady, New York. Rept. no. KAPL-2169, 25 Sep 1961, 43p. (Contract W-31-109-eng-52).

Electrical conductivity and Hall and Seebeck coefficient changes of n-type PbTe were extended to reactor irradiations of 10×10^{19} cm² neutrons with energy greater than 1 Mev and thermal neutron doses of 10^{21} cm². Similar properties were measured

for extruded p-type PbTe after reactor irradiations of 10^{19} cm^{-2} for fast neutrons and $3 \times 10^{20} \text{ cm}^{-2}$ for thermal neutrons. Sample temperatures during irradiation were $60 \pm 20^\circ\text{C}$. Isothermal annealing experiments indicated the simultaneous recovery of conductivity and Hall and Seebeck coefficients from 100 to 170°C and from 140 to 180°C for p- and n-type materials, respectively. The carrier concentration decrease accounted for most of the increase in Seebeck coefficient (increased by factor 1.9). In the annealing process for both materials, there was evidence of a second stage that appeared at low temperature in the p-type and at high temperature in the n-type. After annealing, both materials retained their characteristic band gaps of $\approx 0.32 \text{ eV}$. The irradiated and annealed n-type PbTe exhibited a mobility temperature dependence of $T^{-3/2}$, which was the same as that found for unirradiated material. Small permanent changes caused by transmutations, and comparisons with previous irradiations at lower doses, which indicated a saturation in the radiation damage, are discussed. Also in: Bulletin of the American Physical Society Series II, 6(5):420, 24 Nov 1961.

104.

Corelli, J. C. and Amorosi, D. M.

Characteristics and annealing of neutron

irradiated PbTe. BULLETIN OF THE

AMERICAN PHYSICAL SOCIETY SERIES

II 6(5):420, 24 Nov 1961.

Conductivity and Seebeck and Hall coefficient changes of n- and p-type PbTe were measured after reactor irradiation of $1-10 \times 10^{19} \text{ cm}^{-2}$ of neutrons with energy greater than 1 Mev and thermal neutron doses of $10^{20}-10^{21} \text{ cm}^{-2}$. Isothermal annealing experiments indicate simultaneous recovery of conductivity, Hall and Seebeck coefficient in the temperature ranges 100-170 C and 140-180 C for p- and n-type materials, respectively. The carrier concentration decrease for both materials (factor 5) accounts for nearly the entire increase in Seebeck coefficients (factor 2).

105. Corelli, J. C., Frost, R. T., and
 Amorosi, D. M.
 ANNEALING OF REACTOR RADIATION
 DAMAGE IN LEAD AND BISMUTH
 TELLURIDES. Knolls Atomic Power Lab.,
 Schenectady, New York. Rept. no.
 KAPL-2159, 3 Jul 1961, 75p.
 (Contract W-31-109-eng-52).

Reactor irradiations of specimens of n-type and p-type lead and bismuth tellurides were carried out to neutron doses of 5×10^{19} fast ($E > 1$ Mev) neutrons/cm² and 6×10^{20} thermal neutrons/cm² at an irradiation temperature of $60 \pm 20^\circ\text{C}$. Comparison of pre- and postirradiation electrical properties of duplicate specimens irradiated with and without cadmium shields indicated that, for these exposures, the principal damage is caused by fast neutrons. This confirmed earlier results obtained from similar specimens irradiated to fast and thermal neutron doses one-quarter as great. Comparison of the results of the two experiments indicated that damage caused by fast neutrons tends to saturate at a dose of 1 to 2×10^{19} fast neutrons/cm². Hall coefficient data indicated that the major portion of damage to electrical and thermal conductivity and Seebeck coefficient of n-type PbTe could be attributed to depression of electrical carrier concentration. This is tentatively attributed to a bombardment-induced trapping level 0.037 volts below the bottom of the conduction band. Annealing experiments performed with the irradiated n-type PbTe indicated complete recovery of measured properties for the cadmium-shielded specimen at temperatures in the range of 140 to 200°C . Small unannealable changes in electrical properties of the unshielded specimen were, within experimental and calculational uncertainties, attributable to increases in carrier concentration caused by transmutation-induced increases in iodine doping level. Similar results were obtained in the case of n-type Bi₂Te₃. Damage to p-type PbTe was not completely removed by annealing. Cold-work experiments carried out on this brittle material indicated that the unannealed damage may be caused by effects associated with the encapsulation procedures. The largest changes in electrical properties before annealing were observed in the case of the initially undoped p-type Bi₂Te₃, in which Seebeck and Hall coefficients showed a reversal in sign as a result of the irradiation.

106. Eisen, F. H.
Recovery of electron radiation damage in
n-type InSb. PHYS. REV. 123:736-744,
1 Aug 1961.

Studies of the production and recovery of electron radiation damage in n-type InSb by means of Hall-coefficient and electrical-conductivity measurements are reported and discussed. Irradiations were performed mainly at 80°K, since no recovery was observed between 4° and 80°K. The damage recovered in five well-defined stages with the recovery nearly complete at 320°K. Isochronal and isothermal recovery was monitored in each of the stages, allowing a determination of the activation energies for recovery and a study of the recovery kinetics. None of the recovery kinetics fit any simple models. There is evidence that two lowest-temperature recovery stages involve the annihilation of close interstitial-vacancy pairs and that interactions of primary defects with impurities do not occur. However, the first-order kinetics expected for close-pair recovery is not explicitly observed. A possible explanation for the observed kinetics, involving the independent annihilation of two types of close-pair configurations in the same stage with an electrostatic interaction between the interstitial and vacancy, is proposed.

107. Frost, R. T., Correlli, J. C. and Balicki, M.
Reactor irradiation of PbTe, Bi₂Te₃, and ZnSb.
BULL. AM. PHYS. SOC., SER II 5:420(A),
25 Nov 1960.

Instrumented samples of polycrystalline n-type PbTe and Bi₂Te₃ and p-type ZnSb have been irradiated in the Engineering Test Reactor (ETR) to a total integrated flux-time of $1.2 \cdot 10^{20} \text{ cm}^{-2}$ of neutrons having energies greater than 1 Mev. The corresponding thermal flux time was $6.1 \cdot 10^{20} \text{ cm}^{-2}$. Electrical resistivity and Seebeck coefficient were monitored by means of seven leads attached to each of the three samples, which were located within a cylindrical region in the reactor 1/2 in long and 3/4 in in diameter. Thermal and resonance neutron reactions on tellurium produced iodine approaching the amount used in the initial doping of the n-type materials. Gamma-ray spectroscopy on uninstrumented samples irradiated to comparable flux-times failed to disclose lines due to long-lived daughters of fast neutron-induced reactions. The changes in electrical properties of uninstrumented PbTe and Bi₂Te₃ samples induced by a fast (>1-Mev) neutron flux time of $1.5 \cdot 10^{19} \text{ cm}^{-2}$ are essentially completely annealed in the range of temperature from 170° to 190°C respectively.

108. Huzimura, R. , Ato, Y. , and Oishi, M.
Effects of electron bombardment on germanium.
II. Effects of local irradiation and subsequent
heating. REP. GOVT. INDUSTR. RES. INST.
NAGOYA (JAPAN) 11(2):100-8, Feb 1962.
(In Japanese)

The changes in the electrical conductivity in n-type germanium single crystals due to isothermal annealing after local irradiation by 4.2 Mev electrons were studied here. The specimens were Sb-doped and of 2 to 3 ohm cm. Undoped specimens were about 20 ohm cm, 0.4 to 0.5 mm thick. They were bombarded at about 180°C and heated at 78° and 150°C. To get bombarding electrons of about $4 \times 10^{15}/\text{cm}^2$, a linear accelerator was used. Conductivity of the doped sample at the exposed region showed an ordinary change with integrated flux, but at the unexposed region conductivity decreased after a small increment. Annealing rate of locally irradiated region of samples was larger than that of the uniformly irradiated. (This phenomenon was predominant in the outer area of the exposed region). An application of electric field of about 10 V/cm seemed to affect the changes at both regions. It was concluded that some of the radiation-introduced defects were mobile in the crystals over a large range, contributing to recovery from the damage.

109. Klontz, E. E. , and Mackay, J. W.
Low temperature annealing of electron-
bombarded Ge. BULL. AM. PHYS.
SOC. , SER. II 6:303(A), 24 Apr 1961.

The relative recovery in each of the two stages in low temperature annealing of electron-bombarded Ge was discussed. The lower stage, about 35°K, was associated with recombination of closest stable vacancy-interstitial pairs; the upper stage, about 64°K, was associated with next-closest pairs. The relative amount of annealing in each of these temperature ranges depends on the total flux which the sample receives. For fluxes less than 10^{16} electrons/cm², no appreciable annealing occurs in the 35°K stage. For more than 10^{17} electrons/cm², about half of the recovery is in each stage. The results indicate that the 35°K stage is probably not associated with primary defects. For sufficiently small irradiation, so that the 35°K stage is not observed, it is found that the per cent recovery in the 64°K stage varies with the bombardment energy, from about 10 per cent for 600 kev electrons to about 50 per cent for 1.0 Mev and above. This is consistent with results showing the existence of radiation annealing which is relatively more important at lower energies.

110. Logan, R. A., Augustyniak, W. M. and
Gilbert, J. F.
Electron bombardment damage in silicon
Esaki diodes. J. APPL. PHYS. 32:1201-1205,
Jul 1961.

The density and distribution of states introduced into the forbidden gap by electron bombardment are discussed. The excess current in silicon Esaki diodes has been shown to be a sensitive indicator of these states. Both the effects of bombardment and the annealing properties of the radiation damage have been found to depend upon the specific donor in the n-type region of the diode. The average bombardment dose of 1-Mev electron/cm² needed to increase the excess current density by 1 amp/cm² at a bias of 0.3 v is 1.2×10^{16} for P-doped diodes and 0.8×10^{16} for Sb- or As-doped diodes. Upon annealing in an inert atmosphere, at temperatures in the range 300°-400°C, the bombardment diode is restored to its original characteristics. While the annealing studies reveal novel interactions, they show considerable similarity with other work where the radiation damage was monitored by carrier lifetime or conductivity measurements. Structures observed in the I-V characteristics during the annealing indicate that the bombardment-induced levels at $E_v + 0.27$ and $E_v + 0.06$ are due to pairing of a primary defect (probably a vacancy) with an arsenic and a phosphorus impurity atom, respectively.

111. Logan, R. A., Augustyniak, W., and
Gilbert, J. F.
Electron bombardment damage in silicon
Esaki diodes. BULL. AM. PHYS. SOC.,
SER. II 6:206(A), 20 Mar 1961.

The effects of bombardment and the properties of annealing of radiation damage in Si Esaki diodes in relation to the specific donor in the n-type region of the diode were discussed. The average bombardment dose of 1-Mev electrons/cm² needed to increase the excess current density by 1 amp/cm² at a bias of 0.3v was 1.2×10^{16} for P-doped diodes and 0.8×10^{16} for Sb- or As-doped diodes. The increase in excess current observed at room temperature was the same for bombardments at 78° or 300°K. Upon annealing in an inert atmosphere, at temperatures in the range of 300° to 400°C, the bombarded diode was restored to its original characteristics. The annealing kinetics for the As or Sb diodes were similar to those observed in As-doped Si in lifetime studies, while the P-doped diodes annealed more rapidly. Structures observed in the I-V characteristics during the annealing were also discussed.

112. Logan, R. A. , Augustyniak, W. M. , and Gilbert, J. F.
ELECTRON BOMBARDMENT DAMAGE IN SILICON ESAKI DIODES: APPENDIX A.
Bell Telephone Laboratories, Inc.
Sixth triannual technical note, 1 Nov 1960 -
28 Feb 1961. Rept. no. ASD-TN 61-81,
15 Mar 1961, p. 11-23.

The present work describes the effects of electron bombardment damage and their annealing upon the electrical characteristics of Esaki diodes. The Esaki diodes used in this study were made by alloying aluminum wire containing 1 per cent boron onto n-type silicon, heavily doped with either arsenic, phosphorus, or antimony. The diode was mounted in a Van de Graaff accelerator. The bombardments with 1-Mev electrons were performed in vacuum at either 300 or 78 K.

113. Matsuura, K. , and Inuishi, Y.
Annealing of radiation damage on lifetime in silicon. J. PHYSICAL SOCIETY JAPAN
16(2):339 (1961).

The annealing of carrier lifetime τ in γ -ray irradiated n-type silicon crystals was observed. An Sb-doped, pulled Si crystal showed different dependence on annealing temperature from floating-zoned crystal, having a peak of $1/\tau - 1/\tau_0$ at about 200 C which is not observed with the latter.

114. Matsuura, K. , and Inuishi, Y.
Effect of neutron irradiation on carrier lifetime in Si. J. PHYS. SOC. JAPAN
16:1485, 1961.

Carrier lifetime in silicon as affected by neutron irradiation, also the annealing of this radiation damage are discussed. Graphic representation is made of irradiation of single crystals of n-type Si with thermal neutrons, and of the recombination decay and thermal release components, with and without bias light illumination. Isochronal and isothermal annealing data are also shown.

114A.

Mueller, H.

The effect of phase changes on the annealing behavior of neutron-irradiated crystals. In PROCEEDINGS OF SYMPOSIUM ON CHEMICAL EFFECTS OF NUCLEAR TRANSFORMATIONS, Prague, 1960, v. I, p. 521-526. Vienna, International Atomic Energy Agency, 1961.

Since marked thermal annealing was observed even below the dehydration temperature, these experiments do not provide unequivocal evidence for the validity of the Harbottle-Sutin model, in terms of which the annealing of Szilard-Chalmers systems is caused by thermally induced recrystallization of displacement spikes, with the observable increase in retention constant for all temperatures, and with recrystallization also occurring if the matrix lattice undergoes a phase change.

115.

Rothstein, J.

Evidence for fast damage annealing processes in semiconductor devices. BULL. AM. PHYS. SOC., SER. II 5:197-198(A), 21 Mar 1960.

The exposure of germanium transistors to Godiva II and Triga pulses and the monitoring of I_{CO} and H_{fe} were reported. The I_{CO} response was separated into sum of (a) a current pulse of the same shape as the radiation pulse, (b) a permanent change proportional to the integrated radiation pulse, and (c) a transient decay. Superpositions of (a) and (b) alone gave excellent agreement with the rising edge of the pulse and the beginning of the decay, or with the rising edge of the pulse and the final level, with difference (b) amounts in the two cases. Decay times of approximately 0.1 (10) msec were found for (c) with Godiva (Triga), calculated as decay between the two cases of superposed (a) and (b). (a) is ascribed to gamma induced hole-electron pairs, (b) to integrated neutron damage, (c) to rapidly annealing neutron damage, electronic, surface, or isotope decay effects. Radiation pulse time constants were 0.04(5) msec for Godiva (Triga) and so were separable from device relaxation. The fast decay may be due to recombination of electrons and holes or of close vacancies and interstitials, the slow decay to vacancy-interstitial or surface relaxation, with isotope decay unlikely.

116. Purdue University, Purdue Research Foundation, Dept. of Physics, Lafayette. Indiana. SEMICONDUCTOR RESEARCH. Fifteenth quarterly rept. 1 Feb-30 Apr 1960. Rept. no. PRF-1258. (Contract DA-36-039-SC-71131). ASTIA AD-239 759.

A number of absorption bands in the 9 to 12 micron region were observed in irradiated silicon which contains oxygen. Heat treatment at 1000 C decreased the 9 μ oxygen band. When such a sample was subjected to bombardment, the bands were found in much smaller intensity than in samples not subjected to this heat treatment.

117. Tanenbaum, M., and Mills, A. D. Preparation of uniform resistivity n-type silicon by nuclear transmutation. J. ELECTROCHEMICAL SOCIETY 108:171, Feb 1961.

By the capture of a thermal neutron, the natural isotope Si^{30} can be transmuted into the unstable isotope Si^{31} which decays by beta emission with a 2.62 hr half-life to the stable isotope p^{31} . By means of this reaction, donors can be produced in a silicon crystal. Because of the uniformity of flux which can be obtained in large nuclear reactors, this technique lends itself to the preparation of uniformly doped n-type silicon. After irradiation the silicon crystal is heavily damaged by the emitted betas, by the recoil of the decaying Si^{31} , and by the high energy neutrons that are unavoidably present in the reactor. However, this damage can be removed by annealing at temperatures near 600°C. The technique has been used to produce n-type silicon with nominal resistivities between 0.1 and 20 ohm-cm. The resistivity of the resulting crystals was uniform over dimensions of 5cm to within $\pm 5\%$.

118. Watkins, G. D., Corbett, J. W. and McDonald, R. S. Infrared studies of electron irradiated silicon II. BULL. AM. PHYS. SOC. 5:26(A), 27 Jan 1960.

The annealing of the 12 μ band produced in silicon by room temperature irradiation with 1.5 mev electrons (see 6050) was discussed. The first stage ($\sim 300^\circ\text{C}$) consists of the disappearance of the 12 μ band and the emergence of a new band at 11.3 μ of

approximately the same intensity. It is primarily in this stage that the spin resonance center anneals and electrical properties recover. It is clear, however, that the sample has not been returned to its initial state. During subsequent higher temperature annealing ($\sim 500^{\circ}\text{C}$), the 11.3μ band disappears and a succession of bands between 11.3 and 9μ band emerge and disappear. During the second stage the 9μ band associated with oxygen in its original state is also observed to diminish. A model of these annealing stages which is also consistent with the identification of the 12μ band as arising from an oxygen trapped in a lattice vacancy was presented.

119.

Yurkov, B. Ya.

On the theory of annealing of radiation damage.

FIZ. TVERDOGO TELA (USSR) 3(12):3563-70,

Dec 1961. (In Russian)

A new solution is proposed for the mechanism of annealing of electron bombardment damage in Ge and Si. Earlier solutions suggested by Waite were found inadequate.

C - Radiative Recombination

120. Ascarelli, G. and Rodriquez, S.
 Recombination of electrons and donors in
 semiconductors. J. PHYS. CHEM.
 SOLIDS (GB) 22:57-62, Dec 1961.

Calculation of the recombination of electrons in the conduction band of a semiconductor, with ionized donor impurities is described here. The process which the authors have assumed consists in the initial capture of the electron in an excited state of the donor centre followed by a transition to the ground state. This recombination mechanism is most effective in the case in which all transitions are accompanied with emission or absorption of phonons. Earlier theoretical calculations and experiments seemed in reasonably good agreement with calculations and theories presented in this article.

121. Baryshev, N. S.
 Radiative recombination of holes and electrons
 in Pbs, PbSe, and PbTe. SOVIET PHYSICS -
 SOLID STATE 3:1037-1038, Nov 1961.

Thermal equilibrium recombination rates and lifetimes of excess electrons and holes were studied over the temperature interval from 77°K to 522°K.

122. Bertolotti, M. , and Sette, D.
 On recombination processes in neutron-irradiated
 n-type germanium. NUOVA CIMENTO(10)
 20:438-442, 1 May 1961. (In English)

A calculation of minority charge carrier lifetimes in neutron-irradiated n-type germanium, recognizing the presence of damage regions produced by fast secondaries. Results are compared with experimental data.

123. Free carrier capture by flaws.
In Blakemore, J. S. SEMICONDUCTOR
 STATISTICS. Chap. 7, p. 237-249. New York,
 Pergamon Press, 1962. (International Series
 of Monographs on Semiconductors, Vol 3).

Contents of Chap. 7: Flaw capture mechanisms; radiative recombination, p239-241; phonon recombination; Auger recombination; relative probability of the various processes; behavior of the extrinsic lifetime - for phonon-aided recombination, and for Auger recombination; interaction with both bands (valence band as well as the conduction band).

124. Radiative and radiationless recombination.
In Blakemore, J. S. SEMICONDUCTOR
 STATISTICS. Chap. 5, p. 196-213. New York,
 Pergamon Press, 1962. (International Series
 of Monographs on Semiconductors, Vol 3).

Contents of Chap. 5: Physics of both forms of band-to-band recombination; radiative recombination; radiationless (multiphonon) recombination; behavior of radiative lifetime; definitions; variation of lifetime with doping and modulation; dependence of excess generation rate; transient decay; variation with temperature.

125. Band-to-band Auger recombination.
In Blakemore, J. S. SEMICONDUCTOR
 STATISTICS. Chap. 6, p. 214-236. New York,
 Pergamon Press, 1962. (International Series
 of Monographs on Semiconductors, Vol 3).

Band-to-band processes. Quantum-mechanical model embodied in discussion of non-equilibrium recombination rates.

126. Byron, Stanley, Stabler, Robert C., and Bortz, Paul I.
Electron-ion recombination by collisional and radiative processes. PHYSICAL REVIEW LETTERS 8(9):376-379, 1 May 1962.

The authors point out two physical principles that dominate the three-body recombination process and form the basis for a simple general method of calculating both the electron temperature and the net rate of three-body recombination.

127. Curtis, O. L., Jr., and Crawford, J. H., Jr.
Radiation-induced recombination and trapping centers in germanium. II. Annealing in gamma-irradiated antimony - and arsenic-doped material. PHYSICS REVIEW 126(4):1342-1349, 15 May 1962.

Authors found that the annealing behavior of antimony-doped germanium is vastly different from that of arsenic-doped material.

128. Curtis, O. L., Jr., and Crawford, J. H., Jr.
THE CARRIER-RECOMBINATION BEHAVIOR AND ANNEALING PROPERTIES OF RADIATION-INDUCED RECOMBINATION CENTERS IN GERMANIUM. Oak Ridge National Lab., Oak Ridge, Tenn. Rept. no. ORNL-3108, 1 Jun 1961, 116p. (Contract W-7405-eng-26).

An investigation has been made of the carrier-recombination behavior and annealing properties of radiation-induced recombination centers in germanium. A model which explains the experimental results in both n- and p-type material for various sorts of irradiation is presented. On the basis of this model, recombination occurs at an energy level 0.36 ev above the valence band in gamma-irradiated n-type germanium.

129. Curtis, O. L., Jr., and Cleland, J. W.
Monoenergetic neutron irradiation of
germanium. J. APPL. PHYS.
31:423-427, Feb 1960.

The nature of defects induced in Ge by 14 Mev neutron irradiation, and their comparison with damage produced by neutrons from a fission spectrum are discussed. Measurements of lifetime, Hall effect, and resistivity were made. The electron removal rate in high-resistivity, n-type material is $\sim 8/\text{cm}^3$ per incident neutron/ cm^2 , measured at 77°K. Lifetime measurements have been made on n- and p-type material. On the basis of simple recombination theory, assuming no variation of capture probabilities with temperature, the results for n-type material indicate that a recombination level is located 0.32 ev above the valence band near the center of the energy gap. Assuming an introduction rate of recombination centers equal to one-half the electron removal rate in n-type material, the following values of recombination capture cross sections are obtained: $\sigma_n = 2.2 \times 10^{-17} \text{ cm}^2$, $\sigma_p = 6 \times 10^{-15} \text{ cm}^2$, the latter value being correct only within about a factor of two. The ratio of the cross sections, σ_p/σ_n , which is independent of the method of determining the number of recombination centers, is ~ 300 , indicating that the recombination centers are negatively charged. The lifetime measurements for p-type germanium are not so readily analyzed. Possible explanations for observed behavior are discussed.

130. Czachor, A., and Piekoszewski, J.
Effect of reactor fast neutrons on electron-hole
recombination in germanium. JOURNAL OF
APPLIED PHYSICS 32:1837-40, Oct 1961.

131. Davies, L. W., and Storm, A. R., Jr.
Recombination radiation from silicon under
strong-field conditions. PHYS. REV.
121:381-387, 15 Jan 1961.

In an attempt to determine the distribution in energy of hot electrons and holes in silicon placed in an intense uniform electric field, measurements have been made of the spectral distribution of recombination radiation at 77°K (field strengths up to 3700 v cm^{-1}) and at 20°K. No change in the spectrum with field was observed, other than a rise in temperature of 6° at 77°K due to Joule heating at 3700 v cm^{-1} in the sample, from which it was concluded that recombination radiation at these temperatures arises predominantly from the decay of excitons formed from the hot carriers,

and that the excitons have a thermal distribution of energy at the lattice temperature. In addition, results are given for the spectrum of the radiation from avalanche breakdown regions in reverse-biased silicon p-n junctions at 77° and 300°K; no differences were detected in the range of energies 1.0–1.4ev, from which it was concluded that exciton decay does not contribute to the observed radiation at 77°K.

132. Galkin, G. N., Rytova, N. S. and Vavilov, V. S.
Volume recombination of current carriers in
n-type silicon containing radiation-induced
structural defects. SOVIET PHYS. – SOLID
STATE 2:1819–1823, Mar 1961.

Data relating to the capture of current carriers by the deep-lying levels of radiation-induced defects in n-type silicon irradiated by high-energy electrons are presented. The location of the recombination levels and their cross sections for capture of electrons and holes are determined.

133. Komatsubara, K.
On the change of surface states of germanium
by irradiation. JOURNAL OF THE PHYSICAL
SOCIETY OF JAPAN 17(1):62–64, Jan 1962.

The change in electronic behavior of the germanium surface caused by γ -ray or 0.8 Mev electron irradiation has been studied. This change is observed by picturing the field effect patterns of the surface recombination velocity, i.e., S ~ E patterns, on the cathode ray oscilloscope. As the result of this experiment, the surface electric charge gradually increases negatively as irradiation progresses. After the irradiation, a complex structure appears in S ~ E curves. It is assumed by analyzing these curves that either a new surface level appears or level density increases as a result of the irradiation.

134. Komatsubara, K.
On the change of surface states of germanium
by irradiation. JOURNAL OF THE PHYSICAL
SOCIETY OF JAPAN 17:62–9, Jan 1962.
(In English)

The change in electronic behavior of the Ge surface caused by γ or electron irradiation was studied. This change is observed by picturing the field effect patterns of the surface recombination velocity, i.e., S ~ E patterns, on the cathode ray

oscilloscope. The surface electric charge gradually increases negatively as irradiation progresses. After the irradiation, a complex structure appears in $S \sim E$ curves. It is assumed by analyzing these curves that either a new surface level appears, or level density increases as a result of the irradiation.

135. La Guillaume, Benoit C., and Parodi, O.
Radiative recombination in germanium and silicon.
In PROCEEDINGS, INTERNATIONAL CONFERENCE
ON SEMICONDUCTOR PHYSICS. Prague, 1960,
p. 426-31. New York, Academic Press and Prague,
Publishing House of the Czechoslovak Academy of
Sciences, 1961, 1133p.

Measurements were made of the intensities of different emitted wavelengths resulting from radiative recombinations in doped Ge and Si, as a function of temperature. In the temperature range of 2 to 14 K, recombination spectra were obtained for Ge doped with various amounts of P, As, Ga, and In. The greater the percentage of impurity, the greater the displacement of intrinsic wavelengths, for an n-type sample. New levels A, B, and C are formed by the impurity. Level A seems to correspond with the recombination of a free carrier with a carrier bound to the impurity in the 1S state. The emission resulting from levels A and C is comparatively sharp, and does not seem to be caused by free carriers. Findings of previous studies are in agreement with those discovered here for doped Si.

136. Lenchenko, V. M.
Certain questions related to current-carrier
recombination and generation in semiconductors.
IZV. AN UZBSSR, FIZ.-MATE. NAUK
(3):34-42 (1961). (In Russian)

A statistical theory for certain phenomena related to current carrier recombination and generation in semiconductors is proposed. A method, similar to that of A. Einstein, is used to derive the Planck formula for the spectral distribution of thermal radiation. The computations assume the existence of forced transitions due to the effect of phonon and photon fields in addition to the spontaneous recombination transitions. Formulas are obtained for the spectral distribution of the intensity of recombination radiation in the presence of impurity levels (traps, recombination

centers, etc.) in the semiconductor; for the radiation and radiationless recombination rates; for the work function under irradiation of the semiconductor by an external light source, as a function of the current-carrier injection levels, the degree of occupation of the local levels and the depth of their location.

137. Primachenko, V. E., et al.
Investigation of fast and slow electron states
of a real germanium surface. UKRAYIN.
FIZ. ZH. (USSR). 5(3):345-57 (1960).
(In Ukrainian)

The influence of an external electric field on the dark conductivity (the field effect) and the surface recombination of thin Ge plates. The study of the dependence of the field effect both on direct current voltage and on square pulses made it possible to determine separately the parameters of the fast and slow surface states. From the measurements of the surface recombination, it was ascertained which of the fast states are responsible for the recombination. Two standard treatments of germanium surfaces (etching in CP-4 and H_2O_2) were compared. Certain conclusions are drawn concerning the nature of these surface states.

138. Rzhhanov, A. V.
The theory of surface recombination in
semiconductors. FIZIKA TVERDOGO TELA
3(12):3698-3705, Dec 1961. (In Russian).
English translation in Soviet Physics - Solid
State, 3(12):2684-88, Jun 1962.

Calculation of the lifetime of charge carriers in excited levels of a recombination center opens the possibility of explaining temperature dependence of the rate of surface recombination; change in surface recombination upon absorption of various atoms and molecules on the surface of a semiconductor. Photoconductivity in the infrared region and its relaxation is one area suggested for investigation of surface phenomena.

139. Tomashpol'skii, F. G., and Kholuyanov, G. F.
The spectra of recombination radiation in alloyed
p-n junctions of SiC. FIZ. TVERDOGO TELA
(USSR) 3(9):2688-93, Sep 1961. (In Russian).
English translation in Soviet Physics - Solid
State (USA) 3(9):1960-3, Mar 1962.
140. Van Dong, N., and Koch, L.
Effects of fast neutrons on the recombination
processes of electron-hole pairs in germanium
of n and p type. In PROCEEDINGS OF THE
INTERNATIONAL CONFERENCE ON SEMI-
CONDUCTOR PHYSICS. Prague, 1960,
p. 297-298. New York Academic Press and
Prague, Publishing House of the Czechoslovak
Academy of Sciences, 1961. (In French)

The n- and p-type germanium crystals were irradiated by fast neutrons in a reactor at ambient (300°K) and liquid nitrogen (77°K) temperatures. Electric conductivity and Hall coefficient measurements indicate a larger increase in defects in the n-type crystal. Carrier lifetimes were measured as functions of neutron flux and bombardment temperature. The results were analyzed by the Shockley-Read equations for determining the recombination properties produced by the radiation. In the n-type crystals, the results show that electron-hole recombination is located in the lower half of the forbidden energy band. The effective capture cross sections of electron-hole pairs are: $\sigma_n = 10^{-15} \text{cm}^2$ and $\sigma_p = 10^{-15} \text{cm}^2$. In the p-type crystals, the results obtained are in disagreement with the Shockley-Read theory. A study of electron lifetime after annealing suggests a multiple level model. The annealing shows that the recombination centers are restored more in the p-type than in the n-type.

141. Vavilov, V. S., et al.
Radiative recombination in germanium
crystals bombarded by fast neutrons.
SOVIET PHYS. - JETP 10:15-17, Jan 1960.

Data on the infrared spectrum accompanying the recombination of electrons and holes in Ge single crystals are presented. It is shown that with increasing concentration of Frenkel defects caused by fast electron bombardment the relative intensity of the emission band with a peak at 2.35μ also increases. The emission spectrum gives information about the radiation-induced energy levels.

142. Zucker, J., and Conwell, E. M.
The recombination of hot carriers in germanium.
PHYS. CHEM. SOLIDS 22:141-7 (1961).

Decreased photoconductivity is observed following microwave pulse excitation, indicating enhanced recombination in the high field.

143. Zucker, J., and Conwell, E. M.
The recombination of hot carriers.
PHYS. CHEM. SOLIDS 22:149-53 (1961).

Kinetics of recombination of hot carriers, showing the relationship between the change of carrier concentration in the microwave field and the speed dependence of the capture cross sections of recombination centers.

D - Measurements of Electrical and Magnetic Properties

144.

Appel, J.

Interband electron-electron scattering and
transport phenomena in semiconductors.

PHYSICAL REVIEW 125:1815-23, 15 Mar 1962.

The effect of interband electron-electron scattering (electron-hole scattering, light hole-heavy scattering, etc.) on the electrical transport phenomena is studied using a variational method obtained by a generalization of Kohler's variation principle to a multiband conductor. It is assumed that the electronic structure is given by parabolic conduction and valence bands, separated from each other by $\Delta E \gg k_B T$; the valence band may be twofold degenerate; the average occupation numbers of electronic eigenstates are given by Fermi-Dirac statistics; the dynamical interaction between charge carriers is described by a shielded Coulomb potential. Assuming nondegenerate semiconductors, acoustical and optical phonon scattering and ion scattering are considered, besides electron-electron scattering. Quantitative results are obtained for the electrical conductivity, the heat conductivity, and the Seebeck coefficient, including the ambipolar effect. The results can easily be applied to cases of physical interest; hole-hole scattering and mobility of p germanium, inter-carrier scattering and mobility of intrinsic germanium, transient conductivity of charge carriers in germanium produced by short pulses of high-energy electrons, inter-carrier scattering and its influence on the heat conductivity, and the Wiedemann-Franz ratio of intrinsic semiconductors are considered.

145.

Aukerman, L. W., et al.

THEORETICAL AND EXPERIMENTAL STUDIES
CONCERNING RADIATION DAMAGE IN SELECTED
COMPOUND SEMICONDUCTORS. Battelle Memorial
Institute, Columbus, Ohio. Rept. no. ARL-62-343,
May 1962, 56p. (Contract nos. AF 33(616)-3747
and AF 33(616)-8064).

An investigation was made of the effects of fast neutron bombardment on the electrical properties of semiconductors, particularly GaAs. Also studies were made of the effects of fast neutron bombardment on the performance of Esaki diodes of Ge, Si, and GaAs. Annealing and optical absorption experiments revealed further data on irradiation damage resulting from neutron irradiation and electron irradiation. Theoretical consideration is given to scattering cross sections for atomic penetration problems.

146. Botvinkin, O. K. , and Vorob'eva, O. V.
Effect of radiation on the electric conductivity
of semiconductor films. STEKLO I KERAM
19(1):4, Jan 1962.

Report of experiments conducted.

147. Bredov, M.M. , et al.
The effect of the type of ions on the nature of
changes on electrical properties of semicon-
ductor surfaces produced by irradiation with
ions of medium energies. SOVIET PHYSICS -
SOLID STATE 3(1):195-199, Jul 1961.

The authors report a study of changes in the current-voltage characteristics of W-Ge and W-Si point contacts, due to irradiation with atomic oxygen and molecular nitrogen ions of 5 and 10 kev energies. There was a considerable difference between the effects of O and N₂ ions on the forward and reverse currents and on the rectification factor.

148. Buras, B. B. , et al.
ELECTRICAL CONDUCTIVITY CHANGES
OF n-TYPE GERMANIUM BOMBARDED BY
REACTOR FAST NEUTRONS. Polish Academy
of Sciences, Institute of Nuclear Research,
NP-8152. Rept. no. 101

The electrical conductivity changes of n-type germanium bombarded by fast neutrons from the reactor at Swierk were studied, and the position of the energy level in the forbidden band of the shallow traps (0.206eV below the conduction band) caused by fast neutron bombardment was established. The results are in agreement with those of Cleland, Crawford and Pigg obtained with germanium of higher conductivity and using a slightly different calculation approach.

149. Buras, B., and Suwalski, J.
 IN-PILE HALL COEFFICIENT MEASUREMENTS
 OF GERMANIUM BOMBARDED BY FAST
 NEUTRONS. Polish Academy of Sciences,
 Institute of Nuclear Research, NP-8667.
 Rept. no. 133/1-B, 1960.

The Hall coefficient and the electrical conductivity of germanium bombarded by fast neutrons from the "EWA" reactor have been investigated. The measurements indicate the presence of fast holes.

150. Corelli, J. C., and Frost, R. T.
 Changes in the thermoelectric properties of
 PbTe, Bi₂Te₃ and ZnSb during irradiation.
 BULL. AM. PHYS. SOC., SER. II
 5:420(A), 25 Nov 1960.

An instrumented in-pile experiment previously described has yielded the following changes. The Seebeck coefficient of the n-type Bi₂Te₃ sample increased by $\approx 10\%$ during the irradiation while the resistivity was increased by a factor of ~ 2.8 with no significant changes for fast ($> 1\text{-Mev}$) flux times greater than $5 \times 10^{19} \text{ n/cm}^2$. In the case of p-type ZnSb the resistivity increased by a factor of ~ 12 with no large changes resulting beyond a fast flux time of $6 \times 10^{19} \text{ n/cm}^2$. The p-type ZnSb converted to n-type after an accumulated fast flux time of $\sim 1.6 \times 10^{17} \text{ n/cm}^2$, and thereafter its Seebeck coefficient exhibited a gradual increase of $\approx 15\%$ with increased in-pile time. The resistivity of n-type PbTe increased by a factor of ~ 25 after a total accumulated fast flux-time of $1.2 \times 10^{20} \text{ n/cm}^2$ with no large changes observed for fast flux-times greater than $\sim 6 \times 10^{19} \text{ n/cm}^2$. Auxiliary experiments suggest that a significant part of resistivity increases for all samples because of stress-induced damage during reactor power transients. In some cases temperatures during irradiation were near the annealing threshold for PbTe and Bi₂Te₃.

151. Corelli, J. C. , and Frost, R. T.
 THE EFFECTS OF REACTOR IRRADIATION
 ON THE THERMOELECTRIC PROPERTIES
 OF LEAD AND BISMUTH TELLURIDES.
 General Electric Company, Knolls Atomic
 Power Laboratory, Schenectady, New York.
 Rept. no. KAPL-2091, 1 Apr 1960.
 (Contract W-31-109-eng-52).

Commercially available specimens of polycrystalline n- and p-type lead telluride and n- and p-type bismuth telluride were irradiated in the Engineering Test Reactor at The National Reactor Test Station at Idaho Falls, Idaho. The preirradiation thermoelectric properties are compared to the postirradiation properties. Duplicate samples irradiated with cadmium shields allowed a search to be made of the effects of transmutation.

Total integrated flux-times of 1.5×10^{20} neutrons/cm² (thermal) and 1.6×10^{19} neutrons/cm² (fast, i. e. , for neutrons having energies greater than 1 Mev) are accumulated by the specimens during irradiation. The specimen temperature during irradiation was $60 \pm 20^\circ\text{C}$.

152. Curtis, O. L. , and Cleland, J. W.
 Monoenergetic neutron irradiation of germanium.
 JOURNAL OF APPLIED PHYSICS 31(2):423-427,
 Feb 1960.

A study has been made on 14-Mev neutron-irradiated germanium, using lifetime, Hall, and resistivity measurements to determine the nature of the radiation-induced defects and to compare the damage with that produced by neutrons from a fission spectrum.

153. Fomina, V. I.
Investigations of induced conductivity in thin
 Sb_2S_3 and Sb_2Se_3 layers. SOVIET PHYS. -
SOLID STATE 3:510-512, Sep 1961.

The results of an investigation of electrical conductivity induced by electron bombardment in Sb_2S_3 and Sb_2Se_3 layers are reported. The dependence of the amplification factor on the electron energy in the exciting beam, current-voltage characteristics of the dark and induced currents, and the dependence of the induced current in the exciting beam were studied. The effect of temperature on all these dependences and on the induced current was also noted.

154. Glanz, G., Olteanu, I., and Dutescu, N.
Facilities used for studying the electrical
properties of semi-conductors exposed to
nuclear radiation. INTERNATIONAL ATOMIC
ENERGY ASSOCIATION Preprint SM-25/10.
11p. (In Russian) (To be published in the
Proceedings of the IAEA Symposium on Radiation
Damage in Solids and Reactor Materials held in
Venice, Italy, 7-11 May 1962.)

Two facilities are described for studying the electrical properties of semi-conductors exposed to nuclear radiation inside the 200 kw reactor (VVRS type) in the Institute of Atomic Physics, Bucharest. With the first facility, samples can be irradiated at ambient temperature or at higher temperatures. It can also be used for: (a) simultaneous irradiation of a number of samples in identical conditions; (b) cooling samples during irradiation by a jet of cold compressed air; (c) inserting and extracting samples while the reactor is operating at 2000 kw; (d) remote-controlled placing of samples in different positions in relations to the core, so that they can be exposed to different neutron fluxes. The second facility can be used for irradiating at the temperature of liquid nitrogen, with automatic regulation of the nitrogen flow, thus avoiding the accumulation of liquid oxygen in the coolant.

155. Goldstein, R. A.
 EFFECTS OF ELECTRON BOMBARDMENT
 RATE ON CONDUCTIVITY ON n-TYPE
 GERMANIUM. Office of Technical Services,
 U. S. Department of Commerce, Washington,
 D. C. Rept. no. PB 152 918, 10 Feb 1961.

An investigation of the effects of electron bombardment rate on the conductivity of n-type germanium crystals is reported. Six samples with initial conductivity of about $0.8 \text{ (ohm-cm)}^{-1}$ were irradiated with 4.6 Mev electrons to a total dose of about 2.5×10^{14} electrons/cm², and the change in conductivity was measured as a function of irradiation rate. The decrease in conductivity is shown to be strongly dependent upon the irradiation rate. The carrier removal efficiency, as calculated from the conductivity change after room temperature annealing, was found to increase from 1.77 to 2.34 for irradiation rates of 1.65×10^{15} to 5.12×10^{16} electrons/cm²-sec. The irradiated samples were annealed at temperatures up to 215°C. The annealing behavior of all samples was found to be identical, indicating no differences in defect configuration. Six additional samples were irradiated with 1 Mev electrons to a total dose of about 7.5×10^{14} electrons/cm² at irradiation rates of 6.09×10^{12} to 1.30×10^{15} electrons/cm²-sec. The carrier removal efficiency was found to be independent of irradiation rate below about 10^{14} electrons/cm² sec. A mechanism to account for the observed rate effect is discussed.

156. Goldstein, R. A.
 EFFECTS OF ELECTRON BOMBARDMENT
 RATE ON CONDUCTIVITY OF n-TYPE
 GERMANIUM. Diamond Ordnance Fuze
 Laboratories, Washington, D. C. Rept.
 no. DOFL-TR-868, 25 Oct 1960.

Six samples with initial conductivity of about $0.8 \text{ (ohm-cm)}^{-1}$ were irradiated with 4.6 Mev electrons to a total dose of about 2.5×10^{14} electrons/cm², and the change in conductivity was measured as a function of irradiation rate. The decrease in conductivity is shown to be strongly dependent upon the irradiation rate. The carrier removal efficiency, as calculated from the conductivity change after room-temperature annealing, was found to increase from 1.77 to 2.34 for irradiation rates of 1.65×10^{15} to 5.12×10^{16} electrons/cm²-sec.

Six additional samples were irradiated with 1 Mev electrons to a total dose of about 7.5×10^{14} electrons/cm², at irradiation rates of 6.09×10^{12} to 1.30×10^{15} electrons/cm²-sec. The carrier removal efficiency was found to be independent of irradiation rate below about 10^{14} electrons/cm²-sec.

157. Gorid'ko, N. Ya. , Kuzmenko, P. P. , and
Novikov, N. N.
Change in mechanical properties of germanium
caused by the change of concentration of current
carriers. FIZ. TVERD. TELA 3:3650-6 (1961).

In this investigation of the microhardness of the surface layer of Ge, concentration of current carriers was varied by different means of illumination of the surface, and by the introduction of nonbasic carriers injected from a joint contact. The variation of surface properties observed in Ge illuminated for a long time is felt to be the result of regrouping of dislocations in the sample during the illumination.

158. Gossick, B. R.
THE DIPOLE MODE OF MINORITY CARRIER
DIFFUSION, WITH REFERENCE TO DISORDERED
REGIONS INDUCED IN SEMICONDUCTORS BY
PILE IRRADIATION. Arizona State University,
Tempe, Arizona. Special rept. Jul 1960.
(For presentation at the International Conference
on Semiconductor Physics, Prague, 29 Aug -
2 Sep 1960).

The following relations which refer to semiconductors containing disordered regions are presented: electrical conductivity by minority carriers, including field and frequency dependence; current density and Hall coefficient for both carriers.

159. Grannemann, W. W. , Bechtel, R. , and
Davis, G. , Jr.
SEMICONDUCTOR PROPERTIES OF TITANIUM
DIOXIDE. University of New Mexico, Albuquerque,
New Mexico. Rept. no. PR-13, 28 Jan 1960.
(Contract DA-49-186-502-ORD-779).

Samples of reduced TiO_2 were irradiated with $5 \times 10^{14} \text{ n cm}^{-2}$ $E > 10 \text{ Kev}$ neutrons at the Triga reactor.

160. Gus'kov, Yu. K. , Zvonarev, A. V. , and Klichnova, V. P.
Investigation of the e. m. f. developed when a system of semiconductors containing uranium is irradiated in a reactor. ATOMNAYA ENERGIYA (USSR) 8(72):(1960). (In Russian). English translation in Reactor Science and Technology (GB), 15(4):231-233, Dec 1961.

This is a report of the measurement of electrical properties of samples of a layer of semiconducting uranium oxide, U_3O_8 , in contact with other oxide layers in a nuclear reactor. Charge carriers are generated from fission fragments, and e. m. f. is generated by the p-n contact between the two oxides. Measurements were made of open-circuit voltage, short-circuit current and ohmic resistance of various samples as a function of integrated flux.

161. E. M. I. Research Labs. , Ltd. (Gt. Brit.)
INVESTIGATION OF ELECTRON BOMBARDMENT INDUCED CONDUCTIVITY. Progress rept. no. 1 on Research Proj. RP5-12 for period ending 1 Nov 1961. Nov 1961, 15p.
ASTIA AD-268 525

Investigations concerned the possibilities of employing charges stored in the bulk of a dielectric by electron bombardment induced conductivity in storage devices. Apparatus was constructed for the fabrication of specimens, and for their dc testing in a demountable chamber to establish the parameters for subsequent pulse testing. The materials tried are As_2S_3 , Sb_2S_3 , ZnS , CdS , Sb_2O_3 , SiO and Al_2O_3 . All but alumina were tested as evaporated layers, the alumina being formed by anodisation. CdS was also tested as a single crystal with indium ohmic contacts. The gain reached the very high value approaching 10 to the 10th power, but there appear to be undesirable time effects.

162. Kholuyanov, G. F.
Concerning the radiation for breakdown in
silicon carbide p-n junctions. FIZ. TVERDOGO
TELA (USSR). 3(11):3314-16, Nov 1961.
(In Russian). English translation in Soviet
Physics - Solid State (USA).

The radiation spectra for breakdown were measured over the range 130° - 700°K for energy quanta from 1.2 - 5.8eV and compared with the spectra of recombination radiation.

163. Konopleva, R. F., Ryvkin, S. M., and
Yaroshetskii, I. D.,
Concerning the hole-capture cross section of
defects produced by γ -irradiation. SOVIET
PHYS. - SOLID STATE 2:533-535, Oct 1960.

The dependence of lifetime on gamma-ray irradiation in n-type germanium is discussed and the hole-capture cross section is determined. The Shockley-Read expression for lifetime is used, assuming that for each defect two adjacent charged states produce a single level which has the greatest significance in recombination. An average value of $3.8 \times 10^{-15} \text{ cm}^2$ for hole-capture cross section is obtained, which is the same order of magnitude as that resulting from defects produced by neutron irradiation.

164. Konovalenko, B. M., Ryvkin, S. M., and
Yaroshetskii, I. D.
Radiation defects in n-Ge caused by fast
electrons. FIZ. TVERD. TELA 4:379-82
(1962)

Study of the temperature dependence of the Hall coefficient in n-type Ge irradiated by fast electrons, with determination of the number of acceptor levels and the cross section for formation of radiation defects.

165. Kravchenko, A. F.
 Certain electrophysical properties of gallium
 arsenide. IZV. VUZ, FIZIKA 3:80-87 (1961).
 (In Russian). English abstract in Solid State
 Abstracts, 2(5-6) Aug-Sep 1961.

Studies on the temperature dependence of the electrical conductivity, the thermal EMF and the Fermi level of gallium arsenide with different conductivities are reported. The effective mass and hole and electron concentrations are determined. The dependence of the Hall constant on the temperature and magnetic field is investigated. The mobility and its temperature dependence are determined. A comparison is made between experimental results and theoretical computations and certain considerations on the mechanism of current carrier scattering are given.

- 165A. Kroemer, H.
 Microwave stimulated resistance oscillations
 in germanium at 4°K. BULLETIN AMERICAN
 PHYSICAL SOCIETY, SER. II 6:116(A), 20 Mar
 1961.

The electrical resistance of several germanium crystals at 4°K was discussed. The resistance was found to oscillate strongly if the crystals were subjected to a microwave field, in addition to being illuminated. The oscillations consist of regularly spaced short pulses (about 3 μ sec long) rather than being sinusoidal. The oscillations set in abruptly at a certain microwave power level. They disappear again at higher powers, before ionization breakdown occurs. The pulse repetition frequency is proportional to the illumination level, typical frequencies being in the kilocycle range. The effect was found in both n- and p-type germanium, and for several crystal orientations. It is believed to be due to a change in carrier mobility through microwave heating which in turn produces a change in the microwave coupling. In this way a thermal runaway occurs, leading to relaxation oscillations.

166. Lehrer, N. H.
**STUDY OF BOMBARDMENT-INDUCED
 CONDUCTIVITY MATERIALS.** Interim
 scientific rept no. 5, 15 Nov 1961 -
 14 Jan 1962. Hughes Aircraft Co.
 14 Jan 1962, 12p. (Contract AF 33(616)7563).
 ASTIA AD-273 628.

A report of research performed to obtain theoretical and experimental data concerning enhanced bombardment-induced conductivity which would make possible the development of a direct-view storage tube. Further correlation was needed of a correlation between increasing crystal size and higher value of the conduction ratio. New evidence suggests that factors other than crystal size play a significant role in the bombardment-induced conductivity effect.

167. Lyubin, V. M.
 Measurement of the resistance and surface
 potential of the layers of a semiconductor.
PRIBORY I TEKH. EKSPER. (USSR)
 (4):118-21, Jul-Aug, 1959. (In Russian).
 English translation in Instruments and
 Experimental Techniques (USA),
 4:637-41, Jul-Aug 1959; publ. Jun 1960.

A description of a method for measuring the resistance and surface potential of high-resistance semiconductor layers, based on the irradiation of the surface of the layers with two electron beams. This method makes it possible to study the kinetics of the processes of the charging and discharging of the surface of the semiconductor. Its basic purpose is the investigation of the photoconductivity and cathode conductivity in semiconductor layers used in television transmitting tubes.

168. Matsuura, K. , and Inuishi, K.
Effect of neutron irradiation on carrier
lifetime in silicon. JOURNAL OF
PHYSICAL SOCIETY OF JAPAN
16:1485 (1961).

Single crystal specimens of n-type Si were studied for effects of neutron irradiation and annealing of radiation damage

169. Oblock, V. S. , and Walters, A. E.
THE EFFECTS OF FAST-NEUTRON BOMBARD-
MENT ON MINORITY CARRIER LIFETIME IN
SILICON: APPENDIX B. Bell Telephone
Laboratories, Inc. , Whippany, New Jersey.
Eighth triannual technical note, 1 Jul -
31 Oct 1961. Rept. no. ASD-TDR-62-189,
15 Nov 1961, 101p. (Contract AF 33(616)6235).

Minority-carrier lifetime was measured using the junction-recovery technique. The integrated fast-neutron exposures were determined using sulfur-foil dosimetry. The integrated fast-neutron flux was taken in six steps from 1.0×10^{12} to 1.4×10^{13} neutrons per cm^2 .

170. Parker, W. J. , and Jenkins, R. J.
THERMAL CONDUCTIVITY MEASUREMENTS
ON BISMUTH TELLURIDE IN THE PRESENCE
OF A 2 MEV ELECTRON BEAM. U. S. Naval
Radiological Defense Laboratory, San Francisco,
California. R & D rept. no. USNRDL-TR-462,
2 Sep 1960.

A procedure is described for making thermal diffusivity measurements of semi-conducting materials in the presence of a 2 Mev electron beam. The thermal diffusivity of four samples of bismuth telluride, including both n and p types, is plotted against temperature, and its independence of the electron bombardment with incident

currents up to 15 microamperes/cm² is demonstrated. The thermal conductivity versus temperature is also given for these four specimens. If it is assumed that the specific heat is unaffected by the electron beam, the thermal conductivity, which is equal to the product of the thermal diffusivity and the volumetric heat capacity, is also unaffected.

171. Pfeiffer, W. F.
 GAMMA RADIATION EFFECT ON THE
 ELECTRICAL CONDUCTIVITY OF MATERIALS.
 Rept. no. GNE-59-12. ASTIA AD-215 599.
 (Thesis presented to the Faculty of the School of
 Engineering of the Air Force Institute of
 Technology, Air University, Mar 1959.)
172. Arizona State University, Tempe, Arizona.
 RADIATION EFFECTS IN SOLIDS - AN
 INVESTIGATION OF THE ELECTRICAL AND
 OPTICAL PROPERTIES OF SEMICONDUCTORS
 AND INSULATORS WHICH HAVE BEEN IRRADI-
 ATED BY FAST NEUTRONS. Final rept.
 AT(11-1)715.

This study indicates that TiO can receive a rather large exposure to fast neutron bombardment with little effect on electrical conductivity. The results of this work indicate that an exposure of approximately 10^{17} fast neutrons/cm³ are necessary to produce a noticeable effect in the resistivity of the reduced samples.

173. Robin, J.
 The influence of pressure on some properties
 of semiconductors. J. PHYS. RADIUM
 21:130-140, Feb 1960. (In French).

Work dealing with the pressure dependence of some properties (e.g., electrical conductivity, resistivity of the p-n junction, and the absorption edge of the fundamental band) of certain semiconductors is summarized. The influence of pressure is indicated by the variation of the width of the energy gap sometimes accompanied by the change of electron and hole mobilities.

174. Saftic, B., Varicak, M., and Zuppa, M.
Effect of monoenergetic 14.2 Mev neutron
germanium. PERIOD. MATH. - PHYS.
ASTRON. (Yugoslavia) 15(1-2) 121-3
(1961).

A germanium sample having initial conductivity $0.2837 \text{ ohm}^{-1} \text{ cm}^{-1}$ at 30° C was irradiated with 14.2 MeV neutrons to a total flux of $2 \times 10^{11} \text{ neutrons cm}^{-2}$. Accurate measurements and temperature control made it possible to observe a decrease in conductivity. The final conductivity was $0.2818 \text{ ohm}^{-1} \text{ cm}^{-1}$, a change of less than 1%. Changes of 0.2% can be measured, the authors feel.

175. Skubenko, A. F.
Electrical and photoelectric properties of
single crystals of antimony selenide and
sulphide. III. Electrical and photoelectric
properties of antimony sulphide (Sb_2S_3).
UKRAYIN. FIZ. ZH. (USSR) 6(4):505-13
(1961). (In Ukranian)

176. Sonder, E., and Templeton, L. C.
Part I. Gamma irradiation of silicon.
Levels in n-type material containing oxygen.
J. APPL. PHYS. 31:1279-1286, Jul 1960.

The measurement of the resistivity and Hall coefficient of n-type silicon containing oxygen as a function of temperature before and after a number of successive irradiations in a Co^{60} gamma-ray source is described. A net acceptor level 0.17 ev below the conduction band was observed to result from the irradiation. Its rate of introduction was $7 \times 10^{-4} \text{ traps/cm}^3$ per photon/ cm^2 in 50-ohm-cm material and was about twice that in more heavily doped material ($\sim 2 \text{ ohm-cm}$). Acceptor levels, lying deep within the forbidden gap, were also observed. Their total introduction rate was smaller than that of the 0.17 ev level by a factor of 50. A lowering of the mobility below $\sim 100^\circ \text{ K}$ was also a result of the irradiations. In heavily irradiated samples this lowering of the mobility was much greater than could be explained on the basis of point-charge scattering.

177. Stein, H. J.
 TRANSITORY ELECTRICAL PROPERTIES OF
 n-TYPE GERMANIUM AFTER A NEUTRON
 PULSE. Sandia Corporation, Albuquerque,
 New Mexico. Rept. no. SCR-197, Aug 1960.
 (Reprint published in Journal of Applied Physics,
 31(8):1309-1313, Aug 1960.)

The stability of neutron bombardment damage in Sb-doped Ge has been investigated by making continuous measurements of the electrical conductivity and Hall mobility following a neutron pulse. Measurements were made in the temperature range from 77 to 308 K with a time resolution of 1 second. At temperatures near 195 K an initial decrease in conductivity and mobility was followed by an additional decrease which exhibited nearly second-order kinetics. At 273 K and above, an initial decrease in conductivity and mobility was observed, but was followed by a recovery consistent with an activation energy of 0.68 eV.

178. Suwalski, J., and Buras, B.
 In-pile hall coefficient measurements of
 germanium bombarded by fast neutrons.
In PROCEEDINGS OF THE INTERNATIONAL
 CONFERENCE ON SEMICONDUCTOR
 PHYSICS. Prague, 1960, p. 292-296.
 New York, Academic Press and Prague,
 Publishing House of the Czechoslovak
 Academy of Sciences, 1961. (In English)

The Hall coefficient and the electrical conductivity of germanium bombarded by fast neutrons from a reactor were investigated. Measurements in the neighbourhood of the intrinsic region were made. A fairly good agreement between experimental and calculated Hall curves was obtained by using a three-carrier model. The concentration ratio and the mobility of the light holes were calculated independently from measurements in different magnetic fields.

179. S̄ymashkev̄ych, A. V. , Kot, M. V. , and
Panasjuk, L. M.
Conductivity induced by electron bombardment
in CdTe and ZnSe. UKRAYIN. FIZ. ZH. (USSR)
5(4):504-8 (1960). (In Ukrainian)

Measurements of induced conductivity in thin CdTe films and single CdTe and ZnSe crystals due to bombardment by electrons with energies up to 3-3.5 keV, and investigation of dependence of induced conductivity on current intensity and energy of primary electrons. Induced conductivity rises more rapidly with increase in primary electron energy seemingly due to increased depth of penetration by electrons.

180. Tippins, H. J. , Jr.
MAGNETORESISTANCE OF THE SILVER
HALIDES. Illinois University, Urbana, Illinois.
Technical note no. 10, Dec 1961, 50p.
(Contract AF 24(638)579). (AFOSR-2040)
ASTIA AD-271 393.

A study was made of the effect of a magnetic field on the conductivity, i. e. , the magnetoresistance effect. The detailed behavior of conduction electrons in a solid in the presence of external fields is determined primarily by two factors, the band structure of the material, and the scattering processes which the electrons experience. Comparison of experimental results with the theoretical predictions for various assumed band structures and scattering mechanisms could provide important evidence for the correct band structure and scattering to be associated with the particular material of interest. To obtain the full information available from electronic conduction measurements it was necessary to apply both electric and magnetic fields.

181. van der Does de Bye, J. A. W.
Measurement of decay times of excess carriers
in semiconductors, excited by x-ray pulses.
PHILIPS RES. REP. 15:275-289, Jun 1960.

A method for the measurement of transient decay times of x-ray-excited excess carrier concentrations in homogenous semiconductors is described. Two pulse generators which can deliver short pulses of 80kv and of 150kv are used. These two voltages imply two different effective linear x-ray attenuation coefficients for every substance.

For Ge they are about 20 cm^{-1} and 8 cm^{-1} . Thus the bulk can be excited without much disturbance by surface recombination. Excitation, dissipation, sample geometry, and noise set a minimum to the resistivity of the sample for the production of a clearly visible decay curve on the oscilloscope. For Ge this is between 0.1 and 1 ohm-cm. The measuring apparatus comprises an exponential time base and a decay-curve simulator for the measurements of decay time constants, down to $0.1 \mu\text{sec}$. Measurements performed on copper-doped Ge yield decay times which are also found with chopped light. Some measurements on CdTe are also described.

182. Van Dong, N., Koch, L., and Dinh Tuong, G.
Disordered regions induced in n-type germanium
by fast neutrons at liquid-nitrogen temperature.
FARADAY SOCIETY, TRANSACTIONS
57:1968-1973, Nov 1961.

Germanium samples have been irradiated by fast neutrons at 77 K. Measurements of resistivity and Hall coefficient were performed during the bombardment. The decrease of electron mobility in the range of low neutron dose is in agreement with a defect model recently proposed by Gossick and Crawford. It is found that the mean radius of disordered regions which are p-type is about 50 Å. Each of these regions is surrounded by a space-charge region of much greater size. The contribution of space-charge regions to the initial carrier removal rate is much more important than that due to isolated defects.

183. Van Dong, N, Koch, L., and Ding Tuong, N
Variation of the mobility of electrons in
germanium irradiated at low temperature
by rapid neutrons. COMPTES RENDUS
HEBDOMADAIRES DES SÉANCES DE
L'ACADEMIE DES SCIENCES
253(22):2487-2489, 27 Nov 1961.

Samples of U of the N type were bombarded by rapid neutrons at 77 K. The study of the mobility of electrons in the region of low integrated fluxes revealed the creation of high local concentrations of vacuities in the crystal lattice. (In French).
Variation de la mobilité des électrons dans le germanium irradié à basse température par des neutrons rapides.

184. van Lint, V. A. J., Wikner, E. G., and Miller, P. H., Jr.
High energy electron irradiation of semiconductors. In PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON SEMICONDUCTOR PHYSICS, Prague, 1960, p. 306-8. New York, Academic Press and Prague, Publishing House of the Academy of Sciences, 1961. (In English)

N-type germanium and p-type tellurium were irradiated at 80°K with 25-Mev electrons; n-type floating-zone refined silicon was irradiated at 300°K. Carrier removal rates calculated from conductivity and Hall-effect measurements were 4.0 cm^{-1} for Ge at 80°K, 0.18 cm^{-1} for Si at 300°K, and 4.4 cm^{-1} for Te at 80°K. The electron Hall mobility in Ge decreased significantly during irradiation, although the hole mobility was large when the sample became p-type. The mobility in Te was observed up to a value characteristic of less pure specimens.

185. van Lint, V. A. J., Wikner, E. G., and Miller, P. H., Jr.
HIGH ENERGY ELECTRON IRRADIATION OF SEMICONDUCTORS. General Dynamics Corp., General Atomic, San Diego, Calif. Rept. no. GA-1513, 13 Jul 1960, 6p. (Contract AF 19(604)3899).

N-type germanium and p-type tellurium were irradiated at 80 K with 25-Mev electrons; n-type floating zone refined silicon was irradiated at 300 K. Carrier removal rates calculated from conductivity and Hall-effect measurements were 4.0 cm^{-1} for Ge at 80 K, 0.18 cm^{-1} for Si at 300 K, and 4.4 cm^{-1} for Te at 80 K. The electron Hall mobility in Ge decreased significantly during irradiation, although the hole mobility was large when the sample became p-type. The mobility in Te was observed up to a value characteristic of less pure specimens.

186. van Lint, V. A. J.
Transient radiation effects in semiconductors.
In PROCEEDINGS OF THE SECOND CON-
FERENCE ON NUCLEAR RADIATION EF-
FECTS ON SEMICONDUCTOR DEVICES,
Sep 1959. Cowan Publishing Company, 1960.

The transient conductivity effects in homogeneous semiconductor materials and p-n junction diodes have been observed. In most cases agreement between experimental results and a straightforward theory is satisfactory.

187. Wolff, P. A.
Theory of optical radiation from breakdown
avalanches in germanium. J. PHYS. CHEM.
SOLIDS 16:184-190, Nov 1960.

A theory to explain the spectrum of light emitted from avalanching germanium junctions, in terms of known properties of the band structure and breakdown process in this material, is developed. The low frequency peak in the spectrum is ascribed to intraband transitions by holes near $k = 0$; higher frequency light arises from electron-hole recombinations. Good agreement with experiment is obtained with a carrier temperature of 0.25 ev and a pair production threshold of 1.5 ev. From the intensity ratio of the two parts of the spectrum an estimate of 10^{19} cm^{-3} is made for the carrier density in the radiating regions.

188. Zareba, A.
On β conductivity in germanium (conductivity
of germanium induced by electron bombardment).
ACTA PHYSICA. POLON. (Poland) 21(4):371-387
(1962).

Measurements were made of mean effective energy of electron-hole pair generation and energies of additional current carriers generated. Conclusions are made as to the role of plasmons in the mechanism of induced β conductivity.

D-1: Applied Electrical Field

189. Allen, J. W.
Effect of electric fields on hydrogen-like
excitons. NATURE 187:51(L), 2 Jul 1960.

The use of the electric field at a grain boundary in materials which exhibit long-range photoeffects to determine the role of exciton migration in the long-range effects is discussed. The boundary attracts the excitons through a polarization mechanism and destroys them by an ionization mechanism. The boundary is therefore opaque to excitons but transparent to light. It has been found experimentally that the presence of a grain boundary in high resistivity gallium arsenide does not influence the long-range effects. Therefore in gallium arsenide these effects are not due to exciton migration.

190. Baruch, P.
MOBILITY OF RADIATION-INDUCED DEFECTS
IN GERMANIUM: APPENDIX A. Bell Telephone
Laboratories, Inc., Whippany, New Jersey.
Third triannual technical note, 1 Nov 1959 -
29 Feb 1960. Rept. no. WADC-TN-60-160,
15 Mar 1960, p. 15-18. (Contract AF 33(616)6235).

This investigation attempts to find out whether bombardment-induced defects in germanium are susceptible to motion under an electric field, if so, to measure their mobility. This measurement would help to confirm that the annealing process in germanium occurs by a diffusion controlled mechanism as postulated before on the basis of reaction kinetics. The measurements of junction capacitance were made at liquid nitrogen temperature.

Curves show that acceptor type centers are swept out from the junction where the field is more intense and accumulate near the edge of the space charge layer where the field drops to zero. A detailed analysis shows that the centers, when negatively charged, move with a mobility of 10^{-14} cm²/volt-sec at 70 C, assuming that the centers are singly charged.

191. Bok, J.
Hot electrons in semiconductors. SOLID
STATE PHYS. ELECTRONICS AND
TELECOMMUNICATIONS 1:475-480 (1960).
(In French)

The reactions of n- and p-type germanium and silicon samples having different purities at different temperatures to a high electric field are discussed. Complete current curves have been traced as a function of applied field for about ten samples, from room temperature to the triple point of hydrogen. The effect of the impurities on the mobility of the carriers was found to be the inverse of the effect of phonons; it tends to increase carrier mobility. Also, since several interactions between electrons and phonons can interfere, the derived curves permit a knowledge of the preponderant processes at each temperature. By attempting to show a thermionic emission, it was hoped to find a method permitting a direct knowledge of the temperatures attained by the electrons. Such emission could be observed in silicon when the surface had been specially treated, and measurements along these lines are continuing.

192. Chuenkov, V. A., and K'o-Ming, C.
Generalization of the criterion of breakdown
of semiconductors in a constant electric field.
FIZIKA TVERDOGO TELA 3(9):2794-2803,
Sep 1961. (In Russian). English translation
in Soviet Physics - Solid State 3(9):2039-2045,
Mar 1962.

Investigation of the behavior of semiconductors in a strong electric field, taking into account the thermal effect of the electric current. A criterion of breakdown was obtained for semiconductors; criteria of electric and thermal breakdown are particular cases of that criterion.

193. Davies, W. L.
Hot electrons in semiconductors and their
applications. PROC. IRE AUSTRALIA
22:151-156, Mar 1961.

As the electric field strength in semiconductors is increased, departures from Ohm's law associated with carrier heating in the semiconductor are observed. At sufficiently large fields, avalanche increases in carrier density are observed. A brief survey of electron heating phenomena in semiconductors, and of their application in some useful devices is given. These include avalanche injection diodes, avalanche transistors and p-n-p-n diodes.

194. Dykman, I. M., and Tomchuk, P. M.
Influence of electric field on electron
temperature, electrical conductivity, and
thermionic emission of semiconductors. IV.
Low lattice temperatures. FIZ. TVERDOGO
TELA (USSR) 3(7):1909-19, Jul 1961.
(In Russian). English translation in Soviet
Physics - Solid State (USA), 3(7):1393-9,
Jan 1962.

The method developed earlier is extended to the case of low lattice temperatures. It is shown that in the region of impurity scattering the electron-electron interactions substantially influence not only the symmetric but also the asymmetric part of the distribution function. More general formulae are obtained for the determination of electron temperature and conduction current by taking into account the above mentioned variation of the asymmetric part of the distribution function.

195. Fomin, N. V.
Absorption of infrared radiation by a semi-
conductor in an electric field. SOVIET PHYS. -
SOLID STATE 2:566-568, Oct 1960.

The dependence of the absorption of infrared radiation by current carriers in non-degenerate semiconductors on the angle between the directions of polarization of light and the electric field is considered. It is shown that when $eEl \ll kT$ (where E is the field, l the carrier mean free path) the effect becomes squared with respect to the field.

196. Paige, E. G. C. (RRE)
The drift mobility of electrons and holes in
germanium at low temperatures. J. PHYS.
CHEM. SOLIDS 16:207-219, Nov 1960.

Measurements of the drift mobility of electrons and holes in the temperature range from 20°K to 300°K in samples of germanium containing impurity concentrations from $7 \times 10^{12} \text{ cm}^{-3}$ to $4 \times 10^{15} \text{ cm}^{-3}$ are reported. Conductivity measurements were also made. Below 100°K the observed minority carrier mobility is less than the mobility calculated from the effects of scattering by phonons and ionized and neutral impurity atoms. The discrepancy, which is greater than a factor of 2 in some cases, has been attributed to electron-hole scattering. It is proposed that the unexpectedly large effect of electron-hole scattering is due to a drag exerted on the minority carriers by the majority carriers when an electric field is applied. Qualitative observations on the drift mobility of electrons were made below 20°K. There is no evidence that electrons remain localized about the same minimum in k space for the duration of a transit time ($1/2 \mu\text{sec}$). An extreme example of conductivity modulation of the injected carrier distribution has been observed when impact ionization takes place.

197. Paranjape, B. V.
Microwave heating of electrons in semiconductors.
BULL. AM. PHYS. SOC., SER. II 5:60-61(A),
27 Jan 1960.

Calculations of electron temperature as a function of the applied microwave field and its frequency were presented. The calculations are based on a simplified model which assumes that under the influence of a strong external electric field, electrons are at a temperature T much higher than that of the lattice. Neglecting interaction of electrons with optical modes, it was shown that at high frequencies ($\omega > \omega_c$) of the microwave field the electronic temperature always stays a finite distance above the lattice temperature T_0 . The critical frequency ω_c is given by $2(kT_0/m^*s^2) \omega_c \tau \sim 1$ where τ is the mean collision time at the highest electronic temperature, and s is the speed of sound in the medium. Properties associated with electrons heated by microwaves can be calculated from these results.

198. Prymachenko, V. Ye., and Snitko, O. V.
The effect of an external electric field on
the condenser photo E. M. F. in germanium
and silicon. UKRAYIN. FIZ. ZH. (USSR)
5(4):488-503 (1960). (In Ukrainian).

In their investigation, the authors discovered that the most characteristic feature of the dependence of the stationary photo e. m. f. (V_{ph}) on the external voltage U is the presence of two boundary values of V_{ph} between which V_{ph} varies within a comparatively narrow interval of fields. Their investigation of the dependence of the surface conductivity permitted them to establish dependence of V_{ph} on the curvature of the energy band at the surface. The theory of surface photo e. m. f. is in good qualitative agreement with the experimental results obtained here.

199. Ridley, B. K.
The effect of an electric field on the decay of
excess carriers in semiconductors. PROC.
PHYS. SOC. 75:157-61, Jan 1960.

Effects of transient sweep-out on the decay rate of excess charge carriers in semiconductors are analyzed. It is shown that the transient sweep-out effects increase the decay rate and, if great enough, can affect the form of the decay. Good agreement has been found between the theoretical and experimental results in one sample. It is pointed out that measurement of the sweep-out effect is a sensitive technique for detecting small differences between hole and electron densities in near-intrinsic material since the sweep-out mobility depends upon this difference.

200. Sah, C. T.
Effects of electrons and holes on the transition
layer characteristics of linearly graded p-n
junctions. PROCEEDINGS IRE 49:603-618,
Mar 1961.

The dc theory of p-n junctions, extended for the consideration of the mobile carriers or electrons and holes in the transition region, is discussed. The linearized Poisson-Boltzmann equation is solved by using a linearization parameter α , which is a measure of the relative importance of the fixed, ionized impurity space charge compared with the mobile carrier or electron and hole charges in the transition region of the p-n junction. It is found that both the transition layer width and the transition carrier

capacitance associated with the electrons and holes in the transition region increase exponentially with applied voltage under forward bias condition. A calculation of the recombination-generation current at a forward bias beyond the build-in or diffusion voltage is now possible with the present theory. The dc theory of junction capacitance compares favorably with experimental measurements of a wide variety of nearly linear-graded diffused silicon junctions.

201. Steele, M. C., and Glicksman, M.
Properties of p-type InSb in pulsed high
electric fields. PHYS. REV. 118:474-477,
15 Apr 1960.

The results of high electric field experiments on p-type InSb at 77°K are discussed. It is shown that electron-hole pair creation occurs at electric fields greater than 700 v/cm. When a sufficient number of pairs are created the Hall coefficient changes from positive to negative. The question of whether holes or possibly injected electrons initiate the pair creation is examined in detail. An incipient negative resistance effect in transverse magnetic fields and the absence of any self-pinch effects are also discussed.

202. Stratton, R.
On the theoretical variation of electron mobility
with applied electric field in semiconductors.
SOLID STATE PHYSICS, ELECTRONICS AND
TELECOMMUN. 1:343-355 (1960).

A calculation of the variation of electron mobility with applied electric field is carried out for a covalent semiconductor on the assumption that interelectronic collisions are sufficiently frequent to determine the energy and momentum distribution of the electron gas. This makes it possible to remove the restriction imposed in all previous calculations, i.e., that collisions of electrons with the nonpolar modes of vibration have only been considered for electron energies very much greater than the optical mode phonon energy and have been neglected for electron energies less than the phonon energy. The present calculations are in much better quantitative agreement with experimental results on n-type germanium than those based on the above restriction except at the highest fields ($>3.5 \times 10^3$ v/cm). In this region the nonparabolic nature of the conduction band may affect the results since the calculation is based on a constant effective mass.

203. Vavilov, V. S., and Britsyn, K. I.
The effect of a strong electric field on the
absorption of light by silicon. SOVIET
PHYSIC - SOLID STATE 2:1746-1747,
Feb 1961.

A shift of 150A in the absorption band edge of monocrystalline Si when exposed to a constant external field of 5×10^4 v/cm is discussed. The shift was observed with thin samples of Si, and is attributed to phonon participation in transitions from the valance to the conduction band. The magnitude of the shift and its dependence on the field intensity agree with theoretical predictions. The observed effect apparently has no inertia. A description and diagram of the experimental device are included.

204. Vavilov, V. S.
Radiation ionization processes in germanium and
silicon crystals. (Protsessy radiatsionnoi
ionizatsii v kristallakh germaniia i kpmniiia.)
USPEKHI FIZICHESKIKH NAUK 75(2):263-276,
Oct 1961.

Experiments with single crystals of Si substantiated the action of a superimposed outside electric field on the ionization process. The photoinization study in the basic band of the optic Ge and Si absorption showed that at the sufficiently high photon energy the quantum yield increased to the magnitudes considerably exceeding one. In the photon energy region, many times exceeding the width of forbidden band, the quantum yield is propositional to the photon energy.

205. Yakovlev, V. A.
The theory governing the conductivity of
electrons in the narrow bands of semi-
conductors in a strong electric field.
FIZ. TVERDOGA TELA (USSR) 3(7):1983-6,
Jul 1961. (In Russian). English translation in
Soviet Physics - Solid State (USA) 3(7):1442-5,
Jan 1962.

Computation of the conductivity caused by the effect of a strong electric field on the electron states in the narrow unfilled bands of a semiconductor.

D-2: Applied Magnetic Field

206. Ansel'm, A. I. , and Askerov, B. M.
Thermomagnetic effects in semiconductors in a strong magnetic field in the case of electron scattering on short-range potential. FIZ. TVERDOGO TELA (USSR) 3(12):3668-77, Dec 1961. (In Russian).
207. Askerov, B. M.
The Nernst-Ettingshausen effect in a strong magnetic field allowing for mixed [impurity and phonon] scattering [of carriers in semiconductors]. FIZ. TVERDOGO TELA (USSR) 3(12):3663-7, Dec 1961. (In Russian)
208. Hasiguti, R. R. , Matsuura, E. , and Matsui, K.
Magneto-resistance of γ -irradiated n-type silicon. In PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON SEMICONDUCTOR PHYSICS. Prague, 1960, p. 312-316. New York Academic Press and Prague, Publishing House of the Czechoslovak Academy of Sciences, 1961. (In English)

Magneto-resistance in weak field of γ -irradiated n-type silicon was measured as a function of field strength and field angle at the temperature range of 83 to 290°K. The effective mass ratios were calculated from the angle dependence of magneto-resistance of unirradiated and irradiated specimens.

209. Landsberg, P. T.
Statistical problems in semiconductors - II.
SOLID STATE PHYS. ELECTRONICS AND
TELECOMMUN. 1:436-455 (1960).

The equilibrium distribution of electrons in a semiconductor is discussed, with special attention to the energy-level structure of the impurity centers, and to a possible transition from "localized" to "nonlocalized" electron states for these centers. It is shown that a magnetic field has rather different effects on the electron population in these two cases. Formulas are given for the lifetimes of excess carriers when these are limited by recombination via impurities which represent a whole spectrum of single-electron energy levels. The effect on lifetimes of a magnetic field, and of a transition from localized to nonlocalized statistics, is discussed quantitatively.

210. Suwalski, J., and Malinowski, W.
SCATTERING OF HOLES IN GERMANIUM BY
LATTICE DEFECTS PRODUCED BY FAST
NEUTRON BOMBARDMENT. Polish Academy
of Sciences, Institute of Nuclear Research,
Warsaw. Rept. no. PAN-315/I-B, Apr 1962,
14p.

A continuous in-pile measurement at constant room temperature of the Hall-coefficient of p-type germanium as a function of fast neutron dose irradiation (up to $2 \cdot 10^{16}$ n/cm²) and magnetic field (from 1 to 9 kOe) was performed. The use of a weak and a strong magnetic field enables one to distinguish the roles played by the normal and light holes. It was shown that the changes in mobility of the light holes due to fast neutron irradiation are more pronounced than those for the normal ones. The experimental curves (hole mobility vs. magnetic field) for various irradiation doses were compared with those calculated on the basis of the Conwell-Weisskopf formula and the results of other authors. This comparison has led to the conclusion that the defects represent single rather than double charged scattering centers and enables one to discuss the scattering process.

211. Tippins, H. H., Jr.
**MAGNETORESISTANCE OF THE SILVER
 HALIDES.** Illinois University, Urbana.
 Technical note no. 10, Dec 1961, 50p.
 Rept. no. AFOSR-2040. (Contract
 AF 49(638)579.

The effect of a magnetic field on the conductivity of silver halides is discussed. An attempt was made to determine whether results of magnetoresistance measurements in AgBr were consistent with the assumptions of a spherical conduction band and isotropic relaxation time. A theory was developed based on this model. The results of some preliminary measurements made on AgCl are presented in addition to the data for AgBr. Results are presented in graph form. The data indicated the assumption of a spherical conduction band is valid.

212. Zavadskii, E. A., and Fakidov, I. G.
 Changes of the electrical conductivity of n-type
 germanium in strong and pulsed magnetic fields.
FIZ. METALLOV i METALLOVEDENIE (USSR)
 1:145-7, Jan 1961. (In Russian). English
 translation in Physics of Metals and Metallography
 (USA).

E - Electron Spin Resonance

213. Fan, H. Y.
SEMICONDUCTOR RESEARCH. Purdue
University Research Foundation, Lafayette,
Indiana. Fourteenth quarterly rept. ,
1 Nov 1959-31 Jan 1960. (Contract
DA-36-039-SC-71131). ASTIA AD-235 332.

Several additional lattice absorption bands were observed in electron or neutron bombarded silicon between 9-14 microns. A summary is given of the investigation of electron spin resonance in neutron irradiation silicon.

214. Lee, S. , and Bray, P. J.
Electron-spin paramagnetic resonance studies
of irradiated alumino-silicate glasses. PHYS.
CHEM. GLASSES (GB) 3(2):37-42, Apr 1962.

For several alumino-silicate glasses and for one soda-aluminosilicate glass, ESR spectra were obtained at room temperature and at liquid nitrogen temperature. Neutron irradiation of all the glasses produced essentially the same spectra as did x-ray irradiation, with one exception. Two types of resonances were noted in the alumino-silicate glasses. The soda-alumino-silicate glass showed only the broad asymmetric resonance.

215. Ludwig, G. W.
Electron spin resonance; its use is leading to a
new understanding of impurity centers in semi-
conductors such as silicon. SCIENCE
135(3507):S99-905, 16 Mar 1962.

Defects from radiation damage are treated briefly, along with two other types of defects: (a) shallow donor impurities; (b) transition metal ions. In text and in references, potential of ESR measurements is explored, with results and conclusions so far. Coupled with the standard spin resonance techniques have been studies of electron-nuclear double resonance; also, examination of spectra in the presence of uniaxial stress, electric fields, infrared light.

216. Mitchell, A. C. G. , and Zemansky, M. W.
 RESONANCE RADIATION AND EXCITED ATOMS.
 New York and London. Cambridge University
 Press, 1962. 338p.

217. Nelson, C. M. , and Weeks, R. A.
 Trapped electrons in irradiated quartz and
 silica: I. Optical absorption. JOURNAL OF
 THE AMERICAN CERAMIC SOCIETY
 43(8):396-398, 1 Aug 1960.

Evidence is given for the correlation between an optical absorption band at 2300
 a. u. and an electron spin resonance system developed in quartz after Co-60
 γ -irradiation. The results of bleaching γ -irradiated quartz and silica at 78 K and
 at room temperature are presented and discussed.

218. Seitz, F. , and Turnbull, D.
 SOLID STATE PHYSICS. ADVANCES IN
 RESEARCH AND APPLICATIONS. Vol 13.
 New York, Academic Press, 1962, 493p.

Includes electron spin resonance investigations of impurities and imperfections in
 semiconductors.

219. Watkins, G. D. , and Corbett, J. W.
 Defects in irradiated silicon. I. Electron
 spin resonance of the Si-A center. PHYS.
 REV. 121:1001-1014, 15 Feb 1961.

It is concluded that the Si-A center, a major radiation-damage defect produced in
 "pulled" silicon by a room temperature irradiation, is a lattice vacancy with an
 oxygen atom impurity bringing two of the four broken bonds associated with the
 vacancy. Spin resonance and electrical activity arise from an electron trapped in
 the other two bonds. A molecular orbital treatment of the trapped electron wave-
 function satisfactorily accounts for the observed g tensor, as well as the hyperfine

interaction observed with neighboring 4.7% abundant Si^{29} nuclei. The changes in the spectrum of a sample subjected to uniaxial stress are also described. Under stress, the amplitudes of the individual resonance components (which correspond to different orientations of the defect in the crystal) are observed to change. This results from (1) electronic redistribution of the trapped electrons among the defects, and (2) thermally activated reorientation of the defects themselves under the applied stress. These two effects are separated and a quantitative study of their magnitudes and signs, as well as their rates, is given. The results confirm many of the important microscopic features of the model.

220. Weeks, R. A., and Nelson, C. M.
 Trapped electrons in irradiated quartz and
 silica: II. Electron spin resonance. JOURNAL
 OF THE AMERICAN CERAMIC SOCIETY
 43(8):399-404, 1 Aug 1960.

The correlation of two paramagnetic defects, observed by the electron spin resonance (ESR) technique, with two optical absorption bands produced by γ -ray or neutron irradiation is indicated. The peaks of the two absorption bands fall at ~ 2100 a.u. of 2300 a.u.

F - Photoconductivity, Radiation Induced

221. Arkad'eva, E. N., and Ryvkin, S. M.
Induced infrared photosensitivity in certain
semiconductors. SOVIET PHYS. - SOLID
STATE 2:1704-1705, Feb 1961.

A discussion of induced infrared (2 to 4 microns) photosensitivity in cadmium selenide, cadmium telluride, and antimony selenide (all at 85°K) observed after preliminary illumination with visible light in the intrinsic absorption region. The spectral distribution and time dependence of photoconductivity, are shown for each compound.

222. Dyck, R. H. C
RESEARCH ON INTRINSIC PHOTOCONDUCTORS
(U). RCA Laboratories, Division of Radio
Corporation of America, Princeton, New Jersey.
Quarterly letter rept. no. 1, 21 Nov-31 Dec 1961.
19 Jan 1962, 6p. (Contract DA 44-009-eng-4865).
ASTIA AD-328 716. CONFIDENTIAL REPORT

Photoconductivity of semiconductors and other photosensitive materials, with some treatment of effects of irradiation.

223. Kamoldinov, M. G., and Reikhrudel', E. M.
Photoconductivity and quantum yield in germanium
under the action of x-rays. SOVIET PHYSICS -
SOLID STATE 3(8):1713-1717, Feb 1962.

The influence of X-rays on the electrical conductivity (concentration, mobility, and lifetime of carriers) of a uniform germanium specimen was investigated by taking simultaneous measurements of the conductivity and Hall effect as a function of absorbed radiation dosage. The energy of electron-hole pair production and quantum yield were determined in a wavelength range from 0.248 to 0.062 Å. The photoconductivity increases "superlinearly" with increasing X-ray dose rate.

224. Levenstein, H.
 Proceedings of the 1961 international conference
 on photoconductivity, New York, Aug 21-24.
 J. PHYS. CHEM. SOLIDS (GB) 22:409 Dec 1961.

The conference was sponsored by the International Union of Pure and Applied Physics, the American Physical Society and the Office of Naval Research. Includes radiation effects related to photoconductivity.

225. Michel, A. E.
 Photoconductivity of silver chloride crystals
 under pulsed x-ray irradiation. PHYS. REV.
 121:968-977, 15 Feb 1961.

Studies of the photoconductivity produced by irradiation with $0.2 \mu\text{sec}$ x-ray pulses in AgCl as a function of temperature ($80-280^\circ\text{K}$), x-ray intensity and penetration, field strength, and crystal preparation, undertaken in order to obtain information about lifetimes and mobilities of electrons and holes, are reported. The measurements of electron lifetimes ($\sim 1 \mu\text{sec}$) and mobilities in air-grown crystals are in agreement with those reported in the literature. The photoconductive response can be described by assuming deep electron traps throughout the volume of the crystal and possibly a disturbed surface layer. No hole motion is observed below 250°K ; above that temperature the schubweg per unit field is estimated at $5 \times 10^{-8} \text{ cm}^2/\text{v}$. The electron lifetime in crystals grown and annealed in He is much smaller than in the air-grown samples. Assuming the same mobility in both samples the lifetime at 80°K is $3 \times 10^{-9} \text{ sec}$. At higher temperatures the pulses show long tails, and between 200° and 280°K the saturation time varies exponentially with $1/T$. It is assumed that shallow traps exit ($\sim 0.08 \text{ ev}$) in a thin surface region which otherwise has a long electron lifetime as compared with the bulk of the crystal. Measurements on crystals doped with 20 ppm Cu^+ indicate that the Cu^+ ions do not act as effective electron traps. On the other hand, the presence of 1 ppm Ni ions reduces the lifetime at 80°K to less than $3 \times 10^{-11} \text{ sec}$, indicating a capture cross section of the Ni ion larger than $300(\text{\AA})^2$.

226. Ryvkin, S. M., Khansevarov, R. Yu., and Yaroshetskii, I. D.
A study of impurity photoconductivity in germanium irradiated by gamma-rays. FIZIKA TVERDOGO, TELA 3(10):3211-3219, Oct 1961. English translation in Soviet Physics - Solid State, 3(10) 2331-2336.

Impurity photoconductivity in n-type germanium subjected to gamma radiation was the subject of the investigation. The existence of two independent levels for the radiation defects at $E_c - 0.2$ ev and $E_v + 0.26$ ev was established from the shape of the spectral dependence of the impurity photoconductivity. The kinetics of the impurity photoconductivity was investigated, and the parameters of the level at $E_c - 0.2$ ev were determined. The complicated effects associated with the onset and decay (quenching) of photoconductivity which are observed under combined excitation are explained from a unified point of view.

227. Schultz, M. L., and Forgue, S. V. C
RESEARCH ON EXTRINSIC PHOTOCONDUCTORS
(U). RCA Industrial Tube Products, Lancaster, Pennsylvania. Quarterly letter rept. no. 1, 21 Nov-31 Dec 1961. 18 Jan 1962, 16p. (Contract DA-44-009-eng-4863). ASTIA AD-328 719.
CONFIDENTIAL REPORT

228. Shalpykov, A., and Lobanov, E. M.
Sensitivity of Si photoelements to γ radiation.
(TR. TASHKENTSK. KONF. PO MIRNOMU ISPOL'Z. AT. ENERGII). AKAD. NAUK UZ. SSR 1:271-6 (1961). (In Russian)

229. Ullman, F. G., and Dropkin, J. J.
Infrared enhancement and quenching of
photoconduction in single crystals of
ZnS:Cu. J. ELECTROCHEM. SOC.
108:154-159, Feb 1961.

Reported observation of an ohmic infrared photoconductivity peaking at 0.65 and 1.35 μ at room temperature in synthetic single crystals of ZnS:Cu, with the photocurrents constant with time, no dependent on any previous excitation, and linear with intensity. Both the IR photocurrent and the IR quenching were found to decrease sharply at low temperatures and apparently require thermal activation.

230. Plotnikov, A. F., Vavilov, V. S. and
Smirnov, L. S.
Kinetics of photoconductivity in neutron irradiated
p-type silicon. SOVIET PHYS. - SOLID STATE
3:2363-7, May 1962.

Concentration of defects introduced into p-type silicon by a fast neutron flux. Evaluation of the hole-capture cross sections of these defects leads to conclusions concerning the defect charge.

231. Vavilov, V. S., Plotnikov, A. F., and
Zakhvatkin, G. V.
Infrared absorption of silicon of high resistivity
containing radiation defects. SOVIET PHYSICS -
SOLID STATE 6(6):894-896, Dec 1959. (Russian
original in Fizika Tverdogo Tela 1(6):976, Jun 1959.

The irradiation of silicon monocrystals by fast neutrons causes a sharp decrease in the concentration of current carriers, an increase in transparency beyond the boundary of the basic absorption band, and also the appearance of additional absorption bands in the region of wavelengths exceeding 1.1 μ .

232. Vavilov, V. S., and Plotnikov, A. F.
The photoconductivity of neutron-irradiated
p-type silicon. SOVIET PHYSICS - SOLID
STATE 3(8):1783-1784, Feb 1962.

New data are presented regarding the dependence of the conductivity of silicon for silicon containing radiational defects. The system of energy levels for defects in silicon is completed. Single p-type silicon crystals obtained by the zone-melting method and containing not more than $5 \times 10^{15} \text{ cm}^{-3}$ oxygen impurity atoms were used. The initial resistance before irradiation was about 100 ohm-cm and the predominant impurity was boron. After irradiation, the fast-neutron flux was $\sim 10^{13} \text{ n/cm}^2$; according to the Kinchin-Piz theory, the concentration of displaced silicon atoms should have been about 10^{14} cm^{-3} . Measurements of the electrical conductivity and of the Hall effect showed that the decrease of the hole concentration in the valence band Δp , was (at $T = 300^\circ \text{ absolute}$) $\sim 8 \cdot 10^{13} \text{ cm}^{-3}$. The photoconductivity measurements were made with the aid of a recording spectrograph similar to the IKS-12 at a temperature close to 100 C absolute.

233. Vavilov, V. S., Lotkova, E. N. and
Plotnikov, A. F.
Photoconductivity and infra-red absorption in
silicon irradiated with neutrons. Translation
from the Russian JOURNAL OF THE PHYSICS
AND CHEMISTRY OF SOLIDS 22:31-38.
Great Britain, Pergamon Press, 1961.

For p-type silicon samples, an investigation was made of infra-red absorption and photoconductivity of silicon single crystals, in an attempt to further clarify the nature of radiation damage. It is the feeling of the authors that effects observed in this experiment resulted from the photoionization in the volume of samples, rather than from the photoionization of centers on the crystal surface.

234. Vavilov, S. V., and Plotnikov, A. F.
Spectra and kinetics of the photoconductivity in
neutron bombarded p-type silicon. BULLETIN
OF THE AMERICAN PHYSICAL SOCIETY,
SERIES II 6(5):477, 24 Nov 1961.

New data of the spectral dependence and the kinetics of impurity conduction in neutron-bombarded silicon single crystals are given. The paper investigates p-type silicon containing not more than $5 \cdot 10^{15} \text{ cm}^{-3}$ oxygen atoms, bombarded with a neutron current of an average energy of 1 Mev of the order of magnitude 10^{13} n/cm^2 .

235. Vogl, T. P., Hansen, J. R., and Garbuny, M.
Photoconductive time constants and related
characteristics of p-type gold-doped germanium.
J. OPT. SOC. AM. 51:70-75, Jan 1961.

Use of two different methods to measure the very short photoconductive time constants of p-type gold-doped germanium is described. The first is indirect, using the relationship between the magnitude of generation-recombination noise and carrier lifetimes. The second method is direct, employing a high-speed light-pulsing technique. If no other noise sources are important, the results of the indirect method approach those of the direct method as a lower limit. A combination of such time-constant measurements has been performed on a series of crystals in which impurity densities and carrier concentrations had been evaluated by Hall coefficient and conductivity measurements. From these data quantum yields of carrier generation, and cross sections for photon capture and carrier recombination were evaluated. The photon capture cross section of the 0.15 ev gold acceptor level at 5μ is $1.3 \times 10^{-16} \text{ cm}^2$, averaging $0.9 \times 10^{-16} \text{ cm}^2$ for $2 - 9 \mu$. The hole capture cross section by the Au^+ ion in germanium was found to be $2.3 \times 10^{-14} \text{ cm}^2$.

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