SEMICONDUCTOR ABSTRACTS

Abstracts of Literature on Semiconducting and Luminescent Materials and Their Applications

Volume VI - 1958 Issue

J.J. Bulloff C.S. Peet, Editors

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PREFACE

This year's compilation of Abstracts has been prepared jointly by members of the Solid State Devices Division, the Applied Physics Division, and the Physical Chemistry Division of Battelle Memorial Institute. The Air Force Office of Scientific Research has very kindly sponsored a portion of the work. This sponsorship is greatly appreciated in that it alleviates some of the extra curricular time required of the Battelle staff members. This extra curricular load has been increasing continually due to the increased number of Abstracts each year.

This volume has some innovations involving a more complete subject index and the use of a longer abstract on the first paper of a given subject with subsequent abstracts being somewhat shorter. Also when papers are presented orally and subsequently published, both references are listed with the same abstract. Even with these changes, the number of pages has increased over 1957.

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Persons on the Battelle Administrative staff who aided in the compilation are A. C. Beer, H. L. Goering, R. L. Merrill, E. E. McSweeney, R. O. Stith and L. E. Walkup.

Thanks are due to Joyce Shrum for her long arduous hours of typing. Very special thanks are due to Dr. J. J. Bulloff who again this year assumed the responsibility of organizing and editing the Abstracts, and in addition did most of the literature search.

We also wish to thank the Editors of Science Abstracts for their very generous permission to use selected abstracts without editing. Their help has greatly reduced the amount of time and work in the compilation of the manuscript.

C. S. Peet, Chief
Solid State Devices Division

Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio

FOREWORD

As in previous years, this compilation is under the patronage of The Electrochemical Society, Inc. Differing from previous years, the Air Force Office of Scientific Research has very kindly provided funds for a portion of the compilation. The remainder of the funds were provided by Battelle Memorial Institute with a large voluntary contribution of extra curricular time by the Battelle staff members.

Realizing that these Abstracts are more useful as they are more current, an all out effort is being made to get them published as soon after the end of the calender year as possible.

The organization and editing of this year's Abstracts were again the responsibility of Dr. J. J. Bulloff.

Mr. C. S. Peet is Chairman of the Semiconductor Abstracts Committee of the Electronics Division and again the acting liaison between Battelle and the Electrochemical Society.

Martin F. Quaely, Chairman
Electronics Division

Electrochemical Society
1860 Broadway
New York 23, New York

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INDICES

GERMANIUM

BAND STRUCTURE

1. "PROPERTIES OF SILICON AND GERMANIUM. II.", E. M. Conwell, Proc. Inst. Radio Engrs. 46, 1281-300 (1958). Review 1952-8.

2. "THE ELECTRONIC STRUCTURE OF DIAMOND, SILICON AND GERMANIUM", G. G. Hall, Phil. Mag. 3, 429-39 (1958). The equivalent orbital method of describing the electronic structure of valence crystals, introduced in an earlier discussion of diamond, is extended in various ways. The interactions of more distant bonds are included so that a more detailed description of the electronic structure can be given. The role of the equations as interpolation formulae is illustrated and used to deduce the effective masses of holes for diamond, silicon and germanium. The application of the method to the conduction bands is also considered.

3. "BAND STRUCTURE CALCULATION FOR GERMANIUM", B. Segall, International Conference on Semiconductors, Rochester, New York, August 18-22, 1958. The Kohn-Rostoker-Korringa method is applied to the diamond structure. For Ge, the method is accurate and rapidly convergent. The radial function logarithmic derivatives are computed by solving the radial equation with a potential (including the exchange term) which is obtained from the self-consistent solutions of a modified Hartree-Fock problem.

4. "ENERGY BANDS OF SILICON AND GERMANIUM", J. C. Phillips, International Conference on Semiconductors, Rochester, New York, August 18-22, 1958. Experimental information is made the basis of a quantitative sketch of the band structures near the energy gap. If the effect of exchange is taken into account, effective mass data can be used to infer term values of various levels. The limitations of this kind of analysis are discussed.

5. "INTERPRETATION OF THE MAGNETO-ABSORPTION SPECTRUM IN Ge AND InSb", L. M. Roth, B. Lax and S. Zwerdling, American Physical Society Meeting, Chicago, Illinois, March 27-29, 1958. A detailed analysis of the fine structure of the oscillatory magneto-absorption spectrum of the direct transition in germanium was made using the Luttinger-Kohn model of the valence band levels with selection rules $\Delta n = 0, -2$ and additional selection rules for m_i (valence band), and m_s, (conduction band) i.e., $\Delta m = 0$ for $E \parallel B$ and $\Delta m = \pm 1$ for $E \perp B$. The spin splitting of the electron levels gives a g factor of -3. The decrease in curvature of the conduction band was quantitatively determined. The oscillatory magneto-absorption data at $300^{\circ}K$ in InSb was also analyzed taking into account the spin-orbit effect on the conduction levels. The splitting of the first two transmission minima was in good agreement with the theoretical g factor

of -50. A theoretical analysis of the indirect transition magneto-absorption spectrum in Ge indicates a nonoscillatory character. A similar analysis of the magneto-absorption spectrum for the vertical transition between the top of the valence band and the lower splitoff band predicts the existence of both oscillatory and nonoscillatory components. Calculations indicate that the low temperature, high resolution apparatus should detect these two sets of spectra.

6. "FINAL REPORT ON INVESTIGATION OF THE EFFECTS OF THE VALENCE BAND DEGENERACY ON THE CONDUCTION PROCESSES IN GERMANIUM", A. C. Beer, F. J. Reid, G. L. Kendall, and R. K. Willardson, Tech. Document AFOSR-TR-58-9; ASTIA Document AD 148 077, Contract No. AF 18(603)-39, December 31, 1957. Hall effect and magnetoresistance vs. magnetic field and temperature for extrinsic region of p-Ge of 0.01-50 ohm-cm room temperature resistivities can be used in 2-band model to determine actual and lattice mobilities, impurity scatter parameter, extrinsic carrier concentrations, and total ionized impurities. Even for purest Ge scatter occurs at all temperatures in the extrinsic region. Large size of low temperature lattice mobilities suggests $T^{-5/2}$-type dependence. Where impurity scatter predominance occurs, theory does not reproduce experimental values. Values of scatter effects, warped energy surface effects and their field dependence, densities of states and mobilities characteristics of each band, and maxima and minima in the Hall coefficient fine structure are as expected from theory and/or cyclotron resonance data.

7. "HALL AND TRANSVERSE MAGNETORESISTANCE EFFECTS FOR WARPED BANDS AND MIXED SCATTERING", A. C. Beer and R. K. Willardson, Tech. Document AFOSR-TN-58-98; ASTIA Document 148 147. Contract AF 18(603)-39; December 30, 1957. Transport integrals for warped bands were evaluated by McClure's method for relaxation times determined by mixed scatter from acoustic phonons and ionized impurities. Hall and transverse magnetoresistance coefficients were calculated for cyclotron resonance parameters of Ge and Si. For Ge, data are consistent with the observed slow:fast hole density-of-states 4 per cent ratio and the fine structure, especially the 1-2 kgauss Hall coefficient impurity-dependent minimum at 80°K, but for Si the different behavior observed is predicted.

8. "PRESSURE AND TEMPERATURE DEPENDENCE OF THE EFFECTIVE MASS OF ELECTRONS IN GERMANIUM", M. I. Nathan, W. Paul and H. Brooks, American Physical Society Meeting, New York, New York, January 29-February 1, 1958. Measurements of the pressure dependence of the electrical resistivity of n-Ge at several temperatures where lattice scattering is predominant can be interpreted largely in terms of interband scattering between (111) and (100) minima. However, there remains an explicit dependence of the

effective mass on volume to which an upper limit can be set. The demonstration of a small explicit temperature dependence of the effective mass allows us to deduce the total temperature dependence. The maximum additional temperature dependence of the electron mobility resulting from intravalley acoustic mode scattering is $T^{-0.04}$ much smaller than is required to explain the $T^{-0.16}$ present discrepancy between the simple theory and experiment. It is shown that the effective mass cannot change by more than 4 per cent between 4°K and 300°K. If the large temperature dependence of the average effective mass deduced by other workers from experiments is genuine, it must be the result, not of changes in band curvature, but of deviations from parabolic character of the bands.

9. "STUDY OF THE CONDUCTION BAND OF Ge BY PIEZORESISTANCE MEASUREMENTS", M. Pollak, American Physical Society Meeting, Ithaca, New York, June 19-21, 1958. Piezoresistance measurements have been performed on n-Ge with donor densities from 6×10^{15} cm^{-3} to 3×10^{19} cm^{-3} over the temperature range 77°K to 300°K. The results can be interpreted in terms of the usual model for the conduction band in germanium, provided that statistical degeneracy is taken into account. The density of states required to explain the degeneracy effects corresponds to the four valley model: The absence of any detectable effect caused by electrons in (100) minima shows that these minima are at least 0.11 ev above the (111) minima. Even in the most impure specimens the mobility anisotropy ratio is not reduced by more than a factor of two.

10. "CYCLOTRON RESONANCE OVER A WIDE TEMPERATURE RANGE", D. M. S. Bagguley, J. A. Powell and D. J. Taylor, Proc. Phys. Soc. 70A, 759-62 (1957). By doping Ge with Au, samples were prepared in which the carrier concentration remained reasonably small up to about 90°K, so that cyclotron resonance observations were not obscured by plasma effects. With this material it is found that in the range from 4 to 65°K the heavy holes, as well as the light holes, have practically isotropic effective mass ($m^*/m = 0.30 \pm 0.02$, 0.045 ± 0.002 respectively), and the relaxation time for both is about 0.5×10^{-11} sec independent of temperature. It is estimated that the relative number of heavy and light holes is about 50:1. These figures are compared with those obtained from other data.

11. "THE FERMI LEVEL IN GERMANIUM AT HIGH TEMPERATURES", J. S. Blakemore, Proc. Phys. Soc. 71, 692-4 (1958). Curves are given showing how the position of the Fermi level varies with temperature from 300°K to 1200°K, for several donor and acceptor concentrations between the limits 10^{16} and 10^{20} cm^{-3}. The calculations allow for the variation of the energy gap with temperature.

12. "PREDICTED INTERVALLEY SCATTERING EFFECTS IN GERMANIUM", W. Shockley, Phys. Rev. 110, 1207-8 (1958). Experiments are suggested which involve the injection of electrons in specially orientated n-p junctions and n-p-n transistors at a-c frequencies of the order of the inverse relaxation time for intervalley scattering. The eccentricity of the ellipsoidal energy surfaces in the conduction band can be deduced.

13. "ZEEMAN SPLITTING OF DONOR STATES IN GERMANIUM", R. R. Haering, Can. J. Phys. 36, 1161-7 (1958). The linear Zeeman effect of donor states is calculated in the effective mass approximation as independent of the longitudinal mass characterizing the ellipsoidal conduction-band energy surfaces as long as the Zeeman splitting is small compared to the energy difference. The Zeeman pattern to be expected in Ge is plotted against the angle between the magnetic field and the (100) direction.

14. "THE SCATTERING OF HOLES AND ELECTRONS IN GERMANIUM AND SILICON", G. E. Pikus, Zhur. Tekh. Fiz. 27, 1606-9 (1957); (In Russian); Also Soviet Phys.-Tech. Phys. 2, 1488-90 (1957); (English). For transitions of holes between "light" and "heavy" states in the valence bands of Ge and Si relaxation times for both types of holes are equal, and transitions are quite probable at each act of the scattering process, in accord with cyclotron-resonance data and the failure to observe experimentally different drift velocities for the two types of hole.

15. "MEASUREMENTS OF THE MAGNETIC SUSCEPTIBILITY OF GERMANIUM", W. Duchateau and A. van Itterbeck, Bull. inst. intern. froid, Annexe, 2, 83-9 (1956); (French). The susceptibility of Ge, n-Ge (Sb-doped) and of p-Ge is reported for 2-300°K. The effective electron mass is calculated as 0.141 m_e.

16. "MAGNETIC SUSCEPTIBILITY OF GERMANIUM", R. Bowers, Phys. Rev. 108, 693-9 (1957). The magnetic susceptibility of highly doped Ge was measured between 300° and I.3°K. The results support a 4-ellipsoid model of n-Ge. No appreciable change in the effective masses was observed between room temperature and 1.3°K. No evidence was found for any substantial change in the curvature of the conduction band for energies up to 0.08 ev above the band minimum. Measurements were made of the spin susceptibility of quasi-bound states of electrons and holes in Ge at a carrier density near $6 \times 10^{16}/cm^3$. In each case, the spin susceptibility was found to be almost independent of temperature. It is concluded that there is strong exchange coupling between neighboring impurity centers at this concentration. The susceptibility of high-purity Ge was measured, and found to be independent of temperature below 60°K.

17. "THE MAGNETIC SUSCEPTIBILITY OF SEMICONDUCTORS", R. Bowers, International

Conference on Semiconductors, Rochester, New York, August 18-22, 1958. A review is given of the analysis of magnetic susceptibility measurements for obtaining information concerning the band structure of semiconductors and for experimentally testing the theories of carrier orbital diamagnetism. The measurements on n-Ge cover a temperature range 300°K to 1.3°K and a carrier density range 5×10^{16} to 3×10^{19}/cc. An analysis of the carrier contribution to the susceptibility leads to the following conclusions: (1) There is only a small discrepancy between the observed carrier susceptibility and a theoretical estimate based on the Landau-Peierls formula. (2) Results suggest the conduction band is parabolic to at least 0.08 ev above the band minimum. (3) Results support the 4 ellipsoid model. Similar measurements have been made on n-InSb in order to examine the form of the carrier susceptibility on a solid whose conduction band is known to depart from the single parabolic form. Over most of the measured range, the observed susceptibility is somewhat larger than a theoretical value obtained from the Peierls formula using Kane's calculation of the shape of the conduction band.

18. "FAR INFRARED MAGNETO-OPTIC EFFECTS FROM IMPURITIES IN GERMANIUM", W. S. Boyle, International Conference on Semiconductors, Rochester, New York, August 18-22, 1958. Far infrared transmission experiments on doped germanium samples at liquid helium temperatures have been performed over a range of frequencies which can cause transitions between the ground state of an impurity and either the excited states of the impurity or the levels in the band. The Zeeman splitting of some of the excited states of impurities has been observed and the results at low fields are in agreement with those calculated from the effective masses given by cyclotron resonance. For a constant such that transitions are excited between the ground state and the continuum. Successive maxima of the absorption coefficient are separated in energy by $\hbar\omega_c$, where $\omega_c = \frac{eH}{m^*c}$. At moderately large fields (20 kilogauss) a large number of these oscillations can be clearly resolved. This enables one to determine effective masses with precision and also to observe any variation in mass in moving up the band. Since the transitions all have the same initial state, the separation between successive maxima is a direct measure of the separation between successive Landau levels in any single band.

19 "LOW-TEMPERATURE OSCILLATORY MAGNETO-ABSORPTION UNDER HIGH RESOLUTION", S. Zwerdling, B. Lax and L. Roth, American Physical Society Meeting, New York, New York, January 29-February 1, 1958. The fine structure of the oscillatory magneto-absorption of the direct transition in Ge predicted theoretically has been observed experimentally. The experiments were carried out using magnetic fields up to 39 kilogauss, liquid

helium temperatures, and an infrared grating spectrometer with useful resolving power greater than 20,000. With unpolarized radiation in the photon energy range 0.90 to 1.07 ev, approximately thirty absorption maxima were observed. Polarized infrared radiation with the electric vector first parallel then perpendicular to the magnetic field resolved considerable additional structure. The experimental data are compared to theory. Other magneto-absorption experiments in semiconductors are discussed.

20. "EXCITON ABSORPTION OF THE DIRECT TRANSITION IN GERMANIUM", S. Zwerdling, L. M. Roth and B. Lax, Phys. Rev. 109, 2207-9 (1958). Exciton absorption of the direct transition in germanium has been observed at 77°K, 4.2°K, and 1.5°K with a high-resolution grating spectrometer. The magneto-absorption of the first two exciton lines has been studied up to 38.9 Kg and showed nonlinear behavior at the lower fields. The binding energy of the exciton at zero field was ~0.0025 ev. The experimental binding energy at 38.9 kg was 0.0043 ev. The expected fine structure of the first exciton line, due to degeneracy of the valence band, was not resolved. The broadening of this line at the highest field was approximately threefold.

21. "THE DIRECT AND INDIRECT TRANSITION EXCITONS IN GERMANIUM", S. Zwerdling, L. M. Roth and B. Lax, International Conference on Semiconductors, Rochester, New York, August 18-22, 1958. The direct transition exciton absorption spectrum has been observed in germanium at low temperatures down to ~1.5°K in d-c magnetic fields up to 38.9 kg. From oscillatory magneto-absorption data, the binding energy of this exciton at zero field was found to be approximately 0.002 ev. An additional and unexplained zero field absorption above the energy gap has also been observed. Using the same apparatus and a 6 mm thick sample of germanium, the indirect transition exciton and its Zeeman effect were observed from 77°K down to ~ 1.5°K. The zero field binding energy of the indirect exciton was found to be 0.0025 - 0.0004 ev from the magneto-absorption data. The line width at zero field of approximately 0.0013 ev corresponds to an exciton lifetime of approximately 6×10^{-12} sec. Exciton absorption is presumably a composite of several lines and appears to have fine structure. The mean shift in energy of the indirect exciton absorption at 38.9 kilogauss is approximately 0.0006 ev in fair agreement with the theoretical prediction of the quadratic Zeeman effect for a simplified hydrogenic model.

22. "EXCITONS IN GERMANIUM AND SILICON", G. G. Macfarlane, T. P. McLean, J. E. Quarrington and V. Roberts, International Conference on Semiconductors, Rochester, New York, August 18-22, 1958. Evidence for exciton creation in Ge and Si by indirect and by direct transitions has been obtained from measurements of the absorption spectra. At low levels of absorption fine structure is observed, which is

interpreted in terms of indirect transitions involving the emission and absorption of phonons. For Ge at least three different phonons with energies 90°K, 320°K, 425°K and for Si four phonons with energies 212°K, 670°K and 1420°K contribute to the absorption. Each component is interpreted as being due to the formation of excitons and of free electron-hole pairs. The spectrum of photoconductivity provides evidence for the exciton transitions. The exciton binding energy is found to be about 0.005 ev for Ge and 0.0073 ev for Si. In Si at 4.2°K absorption to the first excited state of the exciton is also observed. The structure of the exciton absorption is smoothed out as the temperature is increased. It is found possible to explain the broadening as due to a temperature dependent relaxation time for the excitons. At high levels of absorption a line structure is observed at low temperatures. This is interpreted as due to direct exciton transitions. The energy dependence of the direct band-to-band absorption above the exciton line can be explained if account is taken of the coulomb interaction of the electron and hole.

LATTICE PROPERTIES

23. "PRECISION MEASUREMENT OF THE LATTICE CONSTANT OF GERMANIUM SINGLE CRYSTALS BY KOSSEL AND VAN BERGEN'S METHOD", G. Mack, Z. Physik 152, 19-25 (1958); (In German). The cube edge is 5.657 35 ± 0.000 05 A at 20.00°C.

24. "ROUTINE CRYSTAL ORIENTATION OF GERMANIUM AND SILICON BY HIGH-INTENSITY REFLECTOGRAMS", G. H. Schwuttke, Sylvania Technologist 11, No. 1, 2-5 (1958). In the routine preparation of single-crystal slabs of Si and Ge, a beam of light reflected from a preferentially etched surface is split into components, the number of components being equal to the number of bounding planes comprising one single etch pit. The pattern of the reflected beam shows the symmetry of the crystallographic directions within 0.5 degree of arc.

25. "PRODUCTION OF ORIENTED GERMANIUM CRYSTALS BY THE CONTACT METHOD", E. Rubesh, Soviet Phys.-Tech Phys. 2, 1538-42 (1957); (English translation); Zhur. Tekh. Fiz. 27, 1655-60. A seed is equilibrated with the surface of the melt, withdrawn and again brought into contact with the melt. A symmetrical Ge crystal grown on the surface of the melt around the seed whose orientation depends on temperature. Then, the crystal is pulled in the usual manner.

26. "CRYSTALLOGRAPHY OF GERMANIUM", G. Novak, Soviet Phys.-Tech. Phys. 2, 1544-54 (1957); (English translation); Zhur. Tekh. Fiz. 27, 1661-70. It is explained why for contact growth from dendrite seeds the [110] and [112] directions are preferred.

27. "SINGLE-CRYSTAL ORIENTATION EFFECTS IN K X-RAY ABSORPTION SPECTRA OF GERMANIUM", J. M. El-Hussaini and S. T. Stephenson, Phys. Rev. 109, 51-4 (1958). Structure on the shortwave side of the K X-ray absorption edge of thin single-crystal Ge was studied; shifts in features 75-280 ev from the edge were discussed. Alloying 7 per cent Si with Ge, changes structure and edge-position.

28. "THE ELECTRICAL PROPERTIES AND REAL STRUCTURE OF SINGLE-CRYSTAL FILMS OF GERMANIUM OBTAINED BY VACUUM EVAPORATION", K. A. Kurov, S. A. Semiletov and Z. G. Pinsker, Kristallografiya 2, 59-63 (1957); (In Russian); See also Abstract 68, "Semiconductor Abstracts" 1957, and Soviet Phys. "Doklady", 1, 604-6 (1956) (English). Films were deposited on glass, corundum and single-crystal germanium. Data are given for electrical conductivity, carrier mobility and Hall effect. The carrier mobility is less in the single-crystal films than in massive single crystals. This is attributed to the presence in the films of defects.

29. "GERMANIUM BICRYSTALS", M. Kikuchi and S. Iizima, J. Phys. Soc. Japan 13, 319 (1958). Ge bicrystals were made from 2 single-crystal seeds. An example where an unexpected 3rd crystal originated at the joint of the [100] [111] grain boundary and the crystal periphery is depicted.

30. GRAIN BOUNDARY CONDUCTION IN GERMANIUM BICRYSTALS", H. F. Matare, B. Reed and O. Weinreich, American Physical Society Meeting, New York, New York, January 29-February 1, 1958. Conductivity measurements on grain boundary layers obtained by controlled growth of bicrystals with two (100) seeds tilted about a (100) axis were carried out in the temperature range between 300°K and 4°K. The low resistivity path of these boundaries was found here without the use of gold doping. While deionization of impurity levels increases the resistivity of the monocrystalline sides by the usual factor of 10^5 to 10^6 from 300° to 4°K, the grain boundary layer maintains an almost constant value of 0.05 ohm-cm over the temperature range, with a linear I-V characteristic. Assuming a uniform width of the conduction region (~100A); the conductivities of the interfaces in n-and p-type material(doped with gallium) differ by less than a factor of 10. Copper diffusion does not change this behavior. Field effect measurements show interface-current modulation.

31. "EVIDENCE FOR VACANCY CLUSTERS IN DISLOCATION-FREE GE CRYSTALS", A. G. Tweet, American Physical Society Meeting, Ithaca, New York, June 19-21, 1958. Ge crystals have been pulled from the melt which contain volumes of the order of cubic centimeters that are free of dislocations, as inferred from counts of the etch pits produced by CP4 on (111) surfaces. When the crystals are grown under appropriate thermal conditions the etching bath attacks the dislocation-free areas more readily than the rest of the