SPACE PROCESSING OF CRYSTALLINE MATERIALS: A STUDY OF KNOWN METHODS OF ELECTRICAL CHARACTERIZATION OF SEMICONDUCTORS

APPENDIX to Final Technical Report (Bibliography)

This study was supported by the
Space Sciences Laboratory
National Aeronautics and Space Administration
Marshall Space Flight Center
Marshall Space Flight Center, AL 35812
under Contract NAS8-30774

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SPACE PROCESSING OF CRYSTALLINE MATERIALS:
A STUDY OF KNOWN METHODS OF ELECTRICAL CHARACTERIZATION OF SEMICONDUCTORS

by

J. G. Castle

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BIBLIOGRAPHY

The enormous volume of semiconductor publications were searched in late '74 for descriptions of experimental techniques for the electrical characterization of semiconductors, aiming especially for those techniques most likely to be suitable for NASA's space processing program. No descriptions of noncontacting techniques with adequate resolution and precision were found in the regular journals, but the trade journals for electronics and optics revealed in 1974 and 1975 several specific references to successful measurements of electrical and/or optical uniformity with the appropriate high precision (circa 1%) and appropriate high resolution (circa microns). The selected bibliography on electrical characterization techniques for semiconductors is given below, arranged alphabetically by first author. The older publications are included for historical interest or theoretical background.

The emphasis for inclusion in this bibliography was on:

1. representative semiconductors -
   mostly Si for the elemental semiconductors,
   mostly GaAs for the III-V compounds, and
   mostly CdS for the II-VI compounds.

2. non-contacting techniques for the standard electrical parameters to suit NASA's need for monitoring crystal growth in space, preferably in real time with high resolution.

It should be noted here (as in the text) that the largest impact of NASA's space processing of semiconductors may well be in those significant applications of special characteristics, such as the negative differential
permittivity for hot electrons in GaAs and the luminescence from SiC which are not well covered in this search.

The attached list includes labels from the categories in Table I of the text. They are summarized in the following Table.

<table>
<thead>
<tr>
<th>Freq Used</th>
<th>DC to RF</th>
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<tr>
<td>El Parameter</td>
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<td>RHO</td>
<td>Bulk Resistance</td>
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<td>Coil Loading (Skin Effect)</td>
<td>Surface Resistance (Skin Effect)</td>
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<td>MU</td>
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<td>Faraday Rotation</td>
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<td>DMU</td>
<td>Gunn Effect</td>
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<td>Permittivity</td>
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<td>TAU and/or IMP or DEF(ects)</td>
<td>Electron Spin Resonance (ESR)</td>
<td>Photovoltage (PV)</td>
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<td></td>
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<td>Cyclotron Resonance</td>
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<td>Photoinduced MW RHO</td>
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<td>Photoluminescence (PL)</td>
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<td></td>
<td>Absorption Spectrum</td>
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</table>

So, for example, an article by G. Feher in 1960 on electron spin resonance (ESR) in silicon would be alphabetized as FEHE60 and labelled with the category TAU-MW or IMP-MW depending on the author’s emphasis. Similarly, the second article by L. W. Patrick and W. J. Choyke in 1965 on SiC photoluminescence (PL) would be listed under PATK65 and labelled IMP-OP.

Review articles and books are labelled as a separate group, called REVIEW.

Includes a variety of techniques for scanning semiconductor surfaces for electrical characteristics.

"Report to the American Physical Society by The Study Group on Radiation Effects on Materials, Section X, Semiconductors."


Summary of the rather extensive information from ESR on point defects in silicon, citing the paucity of defect inventories in other semiconductors and the need for further electrical characterization of defect processes.


Microfiche: AD 674 627

"Methods of Measurement for Semiconductor Materials, Process Co--etc."


Microfiche: AD 681 330.

"Methods of Measurement for Semiconductor Materials, Process Co--etc."


Microfiche: AD 683 808
"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

Microfiche: N69-39759

"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

Microfiche: N69-30167

"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

Microfiche: N70-28987

"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

Microfiche: N70-24156

"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

Microfiche: N71-24975
"Methods of Measurement for Semiconductor Materials, Process Control and Devices."

W. M. Bullis, National Bureau of Standards, Wash., DC, NASA-CR-123167, pp. 54 (October 1971)
Microfiche: N71-38504

"Microwave Methods of Studying Semiconductor Materials."

E. W. Griffin; RADC-TR-71-28(U); February 1971; Cornell University, Ithaca, NY, School of Elec Engr.
Microfiche: AD716869 (3 cards).

"Microwave Engineering."


- Basic theory of wave propagation in circuits, especially mode charts. Basic design considerations for resonant cavities and filter circuits, including shim effect and extensive references.

Book - "Characterization of Semiconductor Materials."


"Physical Characterization of Electronic Materials, Devices and Thin Films."

Microfiche: AD 703275 (1 Card)

- High pressure synthesis of Group IV analog compounds.
"Silicon Device Processing."

Microfiche: N71-17276 (8 cards).

Book - "Defect Electronics in Semiconductors"


- Defects that affect electrical properties of semiconductors are reviewed, especially with respect to their influence and applications in devices. Measurement techniques are summarized in a seventy page appendix.

Book - "Deep Impurities in Semiconductors."


- This book reviews the deep traps formed by a variety of specific impurities in Si and Ge, in GaAs and other III-V compounds. Photoconductivity involving two wavelengths of light and also high field permittivity are discussed, as are techniques for lifetime measurements.

"Resistivity, Mobility and Impurity Levels in GaAs, Ge and Si at 300°K."


- The resistivity and mobility data of GaAs at 300°K have been analyzed by least-square method and plotted as a function of the impurity concentration. The measured impurity levels in GaAs have been presented in graphical form for the most accurate and up-to-date values. For convenient reference the published results for Ge and Si are also presented.
"Transient Method of Measuring Very Low Conductivities Without Contacting Electrodes."


- An experimental procedure is proposed, which amounts to Fourier transforming the frequency depending torque in the Ogawa's torsion pendulum method. This reduces by a factor of the order 100 the fairly long times needed for measuring the very low conductivities of insulating materials.

"Apparatus for the Rapid Scanning of the Seebeck Coefficient of Semiconductors."


"Simple Apparatus for Measuring Thermoelectric Power of Small Samples from 80 to 650K."


"Use of a Thermoelectric Probe in an Investigation of the Diffused Impurity Distribution in Layers."


- This paper reports the results of an investigation of the diffusion profile of zinc in gallium arsenide, which was deduced by measuring the thermoelectric power during successive removal of layers.
WOLF70 "Ionized Impurity Density in \( \eta \)-type GaAs." 


Total ionized impurity densities \((N_D + N_A)\) from \(7 \times 10^{13}\) to \(3 \times 10^{17} \text{cm}^{-3}\) are determined for epitaxial samples of \( \eta \)-type GaAs by analyzing mobility and carrier concentration data as a function of temperature with the Brooks-Herring formula for ionized impurity scattering. This procedure results in the determination of a temperature range within which the effects of other scattering mechanisms are minimal and gives values of \(N_D\) and \(N_A\) which are in good agreement with impurity densities obtained from analyses of the temperature variation of the Hall constant. These results are then used to determine empirical curves relating the impurity density to the \(77^0\text{K}\) Hall mobility. With these data a good estimate of the total ionized impurity concentration in a sample can be determined from Hall constant and resistivity measurements at \(77^0\text{K}\).

RUFF68 "Determination of Resistivity and Hall Coefficient of Semi-conducting Materials Between 80^0\text{K} and 375^0\text{K}." 


MCKI69 "Systematic Errors in Alternating Current Hall Effect Measurements." 

"Contactless Resistivity Meter for Semiconductors."


- This note describes a simple apparatus for the comparative determination of resistivity in the range $10^{-3}$ to 10 ohm cm, using the eddy-current principle. Eddy currents are induced in the specimen by a flat spiral inductor forming part of the tuned circuit of an oscillator working at about 10 Mc/s.

"A Non-Contact Resistivity Meter."


- An instrument is described which can measure the resistivity of slices of semiconducting material. It is suitable for resistivities of the order of milliohm cm. The calibration of the instrument is calculable from theory. Resistivity is indicated by a frequency to which it is linearly related.

"Contactless Induction Method for Electric Resistivity Measurement."


- A new absolute method is developed for measuring electric resistivity in the range of $10^{-8}$ to $10^{+8}$ ohm-cm of a sample of almost arbitrary shape. This method takes into account the effect of self-induced conduction and polarization current. Measurements are made with the specimen placed in a constant rotating magnetic field in such an orientation that it experiences maximum torque and has minimum moment of inertia.

"Direct Determination of Skin Depth by a Radio-Frequency Size Effect."


- A size-dependent absorption peak is observed when single- or poly-crystal Bismuth slabs at liquid Helium temperatures are situated in the tank coil of a marginal radio-frequency oscillator and subjected to a magnetic field H.
"Electrodeless Measurement of Resistivities Over a Very Wide Range."


- Resistivity of electronic conductors, from metals to semiconductors, is determined from the change in grid current of a high frequency oscillator owing to the loading resulting from eddy currents in the sample. A typical calibration curve, made at 15 Mc and covering the range $10^{-8}$ $\Omega$-cm to $10^8$ $\Omega$-cm is given; application to the estimation of sample homogeneity is discussed.

"Measurements of High Resistivities by the Electrodeless Falling Sample Method."


"Measurement of Resistivity Change by a Mutual Inductance Method."


- The resistivity of a nonferromagnetic conductor can be deduced from the change in mutual inductance between two coils when the sample is inserted. A method is described for measuring mutual inductance over a range of frequencies and this can be used to detect change in resistivities of the order of $+10^{-13}$ ohm-cm.

"Contactless Measurement of Resistivity of Slices of Semiconductor Materials."


- In this resistivity measurement, a pair of semicircular measuring electrodes is connected to a series or parallel resonance circuit composed of an inductance $L$ and a variable capacitance $C$. A sample is coupled capacitively with the electrode with no direct contact. The authors' method is similar to the Q meter method in principle, but uses a comparative measurement.
- A method is developed whereby electrical conductivity and dielectric constant of semiconducting and dielectric materials without contacting electrodes can be measured. The principle of this method is that a specimen suspended in a rotating field with a fine fiber is rotated by the torque proportional to the electrical conductivity or the imaginary part of its complex dielectric constant, and the torque exerted on it by a linearly polarized field is proportional to the real part of its dielectric constant.

- A method is proposed for determining the resistivity of semiconductor disks by means of eddy currents. From the solution of the problem of the influence of a conducting disk on a turn carrying a current which varies according to a harmonic law, the relationship is obtained between the magnitude of the resistance reflected into the turn and the electrophysical and geometric parameters of the semiconductor disk. The calculation error was estimated experimentally and does not exceed 10% in comparison with the results of contact measurements performed on single-crystal semiconductor disks.

- Electrodeless methods, based on the inductive coupling of samples to coils, for determining the electrical conductivity, the Hall mobility, and the magneto-resistance of a semiconductor are described. The theory is developed for cylindrical and spherical geometry samples and design considerations and experimental techniques are discussed.

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"Lumped Constants for Small Irises."

H. A. Bethe, MIT Radiation Laboratory, Report 43-22 (March 24, 1943).

- The basic calculation of the constants which describe the microwave coupling through an iris.

"Electrical Characterization of GaAs Single Crystal in Direct Support of M555 Flight Experiment."


- Two methods of obtaining the microwave skin depth, one for mapping flat surfaces and the other for analyzing the whole surface of small single crystal wafers, were developed to the stage of working laboratory procedures. The preliminary 35 GHz data characterizing the two types of space-related single crystal surfaces, flat slices of gallium arsenide and small wafers of germanium selenide, are discussed. A third method of nondestructive mapping of donor impurity density in semiconductor surfaces by scanning with a light beam was developed for GaAs.

"Electrodeless Determination of Semiconductor Conductivity from $TE_{01}^0$-Mode Reflectivity."


- A technique utilizing the $TE_{01}^0$-mode of circular waveguide in a "reflection coefficient bridge."

"High Frequency Conductivity in Semiconductors."

B. Donovan and N. H. March, Departments of Physics, Bedford College, London and University of Sheffield, p. 528 (1956).

- Historical calculation of the electrical conductivity in alternating fields is developed for non-degenerate semiconductors with spherical energy surfaces.
"Noncontact Method of Measuring Temperature Dependence of Electrical Conductivity of Semiconducting Materials."


- A noncontact method of measuring specific resistance of semiconducting samples in a wide range of temperatures (20-800°C) with the use of a super high frequency cavity resonator is described.

"New Microwave Techniques in the Measurement of Semiconductor Phenomena."


- Techniques have been developed using microwave transmission and reflection to determine the physical constants of crystals such as the bulk lifetime, surface recombination velocity, resistivity and dielectric constant. One of the most recent developments involving the profiling of ingot resistivity and lifetime by a microwave reflection method promises to be as accurate and less complicated than the more conventional dc conductivity techniques.

"Reflection of Microwaves from Semiconductors."


- Reflection of microwave energy from a semiconductor is calculated and measured. The wave guide is terminated by a semiconductor-metal sandwich.


- Historical description for measuring the resistivity of semiconductors at centimetre wavelengths.
Comments on Electrodeless Measurements of Semiconductor Resistivity at Microwave Frequencies."

"Determination of the Carrier Mobility and Density in Semiconductors Using a Bimodal Microwave Resonator."

- An analysis is given of the possibility of measuring the mobility and density of free carriers in semiconductors in the microwave range, using a bimodal resonator in a wide range of temperatures and magnetic fields. The results of the calculations are compared with experimental data on n-type Ge.

"Use of a Bimodal Resonator in the Determination of the Mobility of Carriers of the Same Sign but with Different Effective Masses."

- A bimodal resonator could be used to measure the parameters of semiconductors with two types of carrier of the same sign but with different effective masses, such as the mobilities of the light and heavy holes in Ge.

"Potentialities of a Bimodal Resonator in the Measurement of μ of High-Mobility Semiconductors."

- A bimodal resonator with two degenerate TE₁₁₁ modes can be used successfully to measure the parameters of semiconductors at microwave frequencies in a wide range of temperatures and magnetic fields.
"Measurement of the Hall Mobility in \( \eta \)-Type Germanium at 9121 Megacycles."


- The Hall mobility of free carriers in a single crystal of 16 ohm-cm \( \eta \)-type germanium was measured at 9121 Mc in a dual mode resonant cavity at room temperature. A microwave value of 2900 cm\(^2\)/volt sec was obtained in comparison to a measured dc value of 2670 cm\(^2\)/volt sec. The dc measurement was made on a second sample cut from the same germanium crystal.

"Microwave Faraday Rotation: Design and Analysis of a Bimodal Cavity"


- The design and analysis of a bimodal cavity for the observation of microwave Faraday rotation is presented.

"Microwave Transmission Through P-Type Germanium."


- Microwave power transmission for both the circular modes and the linear mode of polarization through p-type germanium has been used to estimate the mobilities due to impurity scattering and thermal scattering.
Experimental data concerning the negative slope-mobility in $\eta$-GaAs are presented. It is generally accepted that the Gum-instability [1] in $\eta$-GaAs is due to a differential negative conductance arising from electron transfer from the high-mobility (000) conduction band minimum towards the low-mobility (100) satellite minima. In this note we should like to report on measurements of the current-voltage characteristic of $\eta$-GaAs by high-power microwaves, using a modification of the technique used by Zucker et. al. [8] for germanium and silicon. This method was chosen since at sufficiently high frequency no build-up of instabilities will be possible because the material is swept very rapidly into and out of the negative-mobility range.

- It is shown theoretically that the average drift velocity of electrons in GaAs as measured by microwave techniques differs substantially from the dc characteristic. This error, arising from electron-energy relaxation effects, has always been neglected in past measurements. The simple model predicts an error of 16% in measured velocity at 35 GHz.

Measurements of the permittivity of bulk $\eta$-type GaAs have been obtained at a frequency of 35 GHz with microwave heating field strengths up to 16 kV/cm. The measurements are in good agreement with predictions of a simple two-valley model using an energy-independent thermal relaxation time $\tau = 1.5 \times 10^{-12}$ sec. The peak value of the large-signal permittivity is found to be considerably smaller than the small-signal high-field values reported in the past. This disparity is substantiated by calculations with the two-valley model. It is felt that the large-signal function measured here is considerably more relevant to LSA-mode circuit design, as well as to calculations of electron parametric operation, than small-signal values.
In order to clarify the reasons of large conflict in the velocity-field characteristics of GaAs among many experiments reported so far the effects of nonuniform conductivity and low field mobility on the velocity-field characteristics are investigated using a microwave-heating technique. Various degrees of nonuniformity are introduced by serial irradiation of electrons on a localized portion of the sample. The results show that the threshold field, peak velocity and negative differential mobility increased with increasing the nonuniformity.

The physical mechanism of the microwave anisotropy due to the hot electron effect in a semiconductor bulk is at first investigated phenomenologically for the case that a relative spatial angle \( \theta \) between a small microwave electric field and a high intensity electric bias field is arbitrary. And then, the microwave anisotropy and the frequency dependence in \( n \)-type GaAs are analyzed by using the Boltzmann transport equations. Conclusively, the microwave anisotropy is especially remarkable in the region of negative resistance.
"Determination of the Impurity Concentration in Germanium from Cyclotron Resonance."


- Cyclotron resonance is widely used in investigations of the mechanism by which the momentum of free carriers in semiconductors is dissipated. The present paper is concerned with the possibility of using cyclotron resonance to determine the concentration of impurities in germanium by measuring the contribution of the scattering by neutral impurities to the cyclotron line width. Such determinations of the impurity concentration have been made already (1, 2). A detailed investigation of the scattering by neutral impurities, reported in (3, 4), is the basis of the method suggested here.

"Raman Spin-Lattice Relaxation of Shallow Donors in Silicon."


This work reports both experimental measurements and calculations of two-phonon Raman spin-lattice relaxation times for shallow donors in silicon, Saturation, line broadening and adiabatic fast passage techniques were used to measure $T_\Sigma (\Delta M = 1, \Delta M = 0)$ between 2 and 300K for P, As, Sb and Bi at 3300 G.

"Spin-Lattice Relaxation of Mn$^{2+}$ in Hexagonal CdS below 4.2°K"


- The spin-lattice relaxation of Mn$^{2+}$ in hexagonal CdS has been studied at $\chi$ band in the temperature range 1.3-4.2°K using inversion-recovery techniques.
DON055  "The Hall Effect in Metals at High Frequencies."


- Historical calculations of the Hall coefficient have been carried through for a metal with two overlapping energy bands, and the variations with frequency and with field strength are shown graphically for certain special cases.

DON054  "The Magneto-Resistance Effect in Metals at High Frequencies."


- Historical description of effect of interband scattering on MW and IR surface resistance.

CHAN73  "Quantitative Piezospectroscopy of the Ground and Excited States of Acceptors in Silicon."

- PA and PL vs. external stress.

FOSS73A  "Radiative Recombination of Electron-Hole Pairs Generated by Two-Photon Absorption in Indium Antimonide."

- Photoluminescence.
FOSS73B "Excess Carriers Induced in Indium Antimonide with a Carbon-Dioxide Laser."

- Photoinduced conductivity.

- An infrared, optical constant model for semiconductors has been used to calculate calibration curves relating carrier concentration in silicon to the pseudo-Brewster angle for several wavelengths, the range of carrier concentrations being limited by the wavelength employed. Experimental results for silicon are presented for a wavelength of 3.391 μm.

- The angle of incidence at which the parallel component of polarized infrared reflected light attains a minimum (the pseudo-Brewster angle, or PBA) is used to determine semiconductor carrier concentrations. A PBA apparatus using a 3.391 He-Ne laser as a polarized light source is described. Experimental results for n- and p-type silicon are compared with plasma resonance and sheet resistance measurements to determine best fit of theoretical calibration curves. Results of reproducibility and correlation studies are also presented.
"Optical Constants and Free Carrier Data of Heavily Doped Semiconductors from Reflection Measurements in the Infrared."


- A method for determining the optical constants of heavily doped semiconductors in the infrared and free carrier parameters is described, which requires one reflectivity measurement only. The method is based upon an analysis of the reflectivity spectrum in the region of the plasma resonance frequency. The analysis takes account of the energy dependence of the relaxation time. This method allows an accurate determination of the index of absorption even for k<0.2 in spite of the simple experimental setup. n and τ data and optical constants so determined are presented for n- and p-type silicon.

"Free-Carrier Reflectivity in Optically Inhomogeneous Silicon."


- Interpretation of reflectivity data from the surface of a semiconductor containing an impurity gradient and, in particular, a p-n junction is of practical importance. Current theories predict a shift in the wavelength of the reflection minimum to shorter wavelengths. In this theory and subsequent measurements, such behavior was not observed; in fact, almost no shift of wavelength occurred even for the most lightly doped and shallow junction samples. The results obtained indicate that the surface free-carrier concentration can be obtained directly from a reflectivity measurement.

"Carrier Lifetime Measurements by the Photoconductive Decay Method."


Microfiche: N73-22685
The disagreement between experimental measurement of the reflectivity minimum of low-mobility semiconductors and simple theory is accounted for by inclusion of the imaginary part of the dielectric constant in deriving the carrier-concentration/plasma-wavelength relationship. Data on the plasma wavelength of p-type gallium arsenide are presented.

When the carrier relaxation time in a semiconductor is estimated independently from reflectivity curves (\(\tau_0\)) and from Hall mobility data (\(\tau_H\)) it is frequently found that \(\tau_0\) and \(\tau_H\) disagree rather markedly. An explanation is often suggested in terms of statistical effects. Since this requires a sufficiently non-degenerate distribution and a strongly dispersive scattering mechanism, we explore another alternative invoking the role of a space charge boundary layer. Two examples are considered and the analysis yields quite reasonable results.

The variation of the position of the infrared reflectivity minimum with carrier concentration was determined from Hall effect and reflectivity measurements, unpublished data of other workers and selected data in the literature. The calibration curve for the determination of concentration from the position of this minimum is given. Concentrations determined from this equation agree with those determined from Hall measurements to \(+12.64\%\) (1 std. dev.).
"Measurement of the Resistivity of Epitaxial Vapor Grown Films of Silicon by an Infrared Technique."


- An infrared reflectivity technique is outlined whereby the reflectivity may be correlated with d-c resistivity of thin vapor deposited epitaxial silicon layers. The theory underlying the method is outlined and calculated curves for different planes of polarization are given. Experimental results are described for a range of resistivities between 0.03-60 ohm-cm. Limitations of the equipment used are discussed and the validity of the method examined.

"Determination of Deep Impurities in Silicon and Germanium by Infrared Photoconductivity."


- A literature search of a PC determination of deep impurity concentrations, noting difficulty with PC when more than one kind of deep trap is present.

"Optical Absorption Edge and Raman Scattering in Ge_x Se_1-x."


- Photon absorption and inelastic scattering.
"Nordestructive Photovoltaic Technique for the Measurement of Resistivity Gradients in Circular Semiconductor Wafers."


- A practical alternative to the four-probe technique for making resistivity gradient measurements along the diameter of a circular semiconductor wafer is described in this paper. This technique, which is based upon the bulk photovoltaic effect of Tauc (5), requires no contact with the flat surface of the wafer and permits a continuous measurement of the resistivity gradient along the wafer diameter to be made.

"Measurement of the Resistivity Inhomogeneity of Photosensitive Semiconducting Materials by the Dark Probe Method."


- The "dark probe" method, proposed in the present paper for measuring the resistivity inhomogeneity of photosensitive semiconducting materials differs basically from the presently available methods. In order to reduce the total resistance the whole sample of length L is illuminated uniformly, with the exception of a narrow strip whose width is X.

"Determination of Electrical Conductivity of Photoconductors Without Contacting Electrodes."


- It is shown that it can be possible to determine electrical conductivity \( \sigma \) of photoconductors and semiconductors without contacting electrodes from measurement of torque exerted on a suspended specimen, by a rotating electric field, \( E(t) \). The experiments were carried out with CdS, S, Se. Those measurements are in good agreement with the literature.

"We have investigated the photomagnetic effect (PME) and photoconductivity (PC) in n-germanium doped with gold as functions of temperature and gold atom concentration."


"The present article explores the applicability of the method of the volume photo-emf for inspecting the homogeneity of semiconductor materials. It is shown that the emf in homogeneous semiconductors arises only due to the space charge, while, in inhomogeneous semiconductors, the emf connected with the non-uniformity of resistivity is added to the emf which is due to the space charge. Recommendations concerning the methods and schemes for plotting the inhomogeneity distribution curves are given. This method can be successfully used for inspecting thin semiconductor plates, for instance, plates of GELS-30/1.5 germanium."


"An apparatus based on the bulk photovoltaic effect, is described by means of which quantitative estimates of the resistivity changes throughout germanium single-crystal samples may be realized. For material that is homogeneous in lifetime, the error may be as little as 3 per cent."
"Optical Probing of Inhomogeneities in $\text{n-GaAs with Applications to the Acoustoelectric Instabilities."

(GaAs) David L. Spears and Ralph Bray; Journal of Applied Physics, Vol. 39#11, 5093 (October 1968).

- A study is presented of the intimate relationship between current instabilities of acoustoelectric origin in $\text{n-GaAs at 77^\circ K}$ and the inhomogeneity in the Ohmic resistivity of the samples. In order to correlate various aspects of the acoustoelectric instabilities with the sample inhomogeneities, two optical probing techniques were developed for determining the Ohmic-resistivity profile with good spatial resolution, $\sim 0.1\text{mm}$. One involves the measurement of the local photoconductance in the sample, which is related to the local dark resistivity; the other method involves the measurement of the change in optical transmission produced by the local thermal shift in the intrinsic absorption edge when the sample is heated by a high current pulse. The change in optical transmission is related to the local resistivity. The acoustic flux distribution in the sample is determined by yet another optical probe, utilizing the modulation in transmission produced by the high acoustic-energy density in the domain. Several aspects of the acoustoelectric effects are themselves useful for gauging the homogeneity of the samples. In particular, the propagating acoustoelectric domain serves as a convenient probe of the carrier concentration. These techniques are applied to the analysis of the form of the current instabilities, the distribution of the acoustic flux in the sample, and the domain-formation process. The presence of a somewhat higher resistance, hence higher acoustoelectric-gain region, at the upstream end near the cathode is shown to contribute to the formation of propagating acoustoelectric domains.

"Determination of Semiconductor Parameters from the Photomagnetic Effect and Photoconductivity."


- The basis is given for an improved variant of the method for determining the parameters of a uniform semiconductor from the photoconductivity and photomagnetic effect response spectra.
"High-Sensitivity Photoconductor Layers."


- High-sensitivity photoconductor "powder" layers and "sintered" layers have been prepared in large-area form, with most of the desirable characteristics of single crystals. At an illumination of 1 ft-c, ratios of photocurrent to dark current as large as $10^6$ may be obtained for both types of layers.

"Photothermoelectric Analysis of Chemically Deposited Cadmium Sulfide Layers."


- Carrier mobilities in the few thousandths cm$^2$/V sec can be reliably inferred from thermoelectric power measurements, considerably smaller than can be determined by standard Hall measurements. Techniques of photothermoelectric analysis are applied to chemically deposited layers of CdS and CdS-CdSe, as prepared, and after photosensitization by impurity diffusion. Photoconductivity in the unsensitized films is due wholly to an increase in mobility in the sensitized films, both carrier density and mobility increase with photoexcitation. The high-light mobility is increased by a factor of $10^2$ by impurity sensitization.

"Double Modulation Method for Hall Effect Measurements on Photoconducting Materials."


- A new double modulation method for photo-Hall mobility measurements on high impedance photoconductors is described. The magnetic field is modulated by rotating the sample in the field and the density of charge carriers is modulated by chopping the light beam which induces photoconductivity. The Hall signal is detected at the sum frequency of the two modulations and a clear distinction in phase and frequency between the Hall signal and different error signals is obtained.
Investigation of the Homogeneity of CdS Crystals Using an Optical Probe.


The internal inhomogeneities in resistivity, electromagnetic coupling constant and electron drift mobility in photoconducting CdS Acoustic Amplifier crystals are measured using an Optical Probe. The Probe consists of a laminar, amplitude-modulated beam of light projected through the crystal and superimposed on the normal illumination. The inhomogeneity information is carried as an a.c. component of the current or ultrasonic signal through the crystal. Results indicate marked inhomogeneities in all these parameters, and point strongly to the fact that the electron drift mobility variation is a primary cause of the resistivity variation in the sample.

Photo-Hall Measurement by an Improved Redfield Method.


Improvements in electrodes and in instrumentation allow measurement of Hall mobilities as low as 1 cm²/V·sec in photoconducting insulators.

Determination of the Mobility in Small Samples of Gallium Arsenide from Magnetoresistive Effects.


A method was developed for the determination of the mobility in n-type GaAs under laser oscillation conditions. The method is based on the dependence of the laser threshold current on the magnetic field. An analysis is made of the physical meaning of the mobilities \( \mu_I \) and \( \mu_m \) found by the threshold-current and the magnetoresistance methods, and of the relationship between these mobilities and the Hall value \( \mu_H \). It is shown that, if the true mobility is taken as \( \mu = \mu_I \mu_m \), it becomes possible to explain much of the experimental data on the dependence of the threshold current and voltage on the transverse magnetic field.
A. K. Walton and P. L. Reimann, Department of Physics, University of Sheffield, p. 1410 (1969).

Measurements of the infrared free carrier dispersion and Faraday rotation in N-type silicon are reported. Combination of the dispersion and Faraday rotation results gives an entirely optically determined room-temperature transverse effective mass of \((0.225 \pm 0.01) m\) yields the carrier concentrations in the specimens. Previous effective mass determinations involving Hall effect experiments must be suspect.


The results of a study of inhomogeneities of \(\rho\) and \(\tau\) in semiconductor crystals are presented. The theory of the bulk photovoltaic effect was used to derive expressions useful in the quantitative evaluation of \(\nabla \rho\) in the various inhomogeneous portions of the crystal using experimentally determined values of the bulk photo-emf and of the photoconductivity of the material.


Photoexcited carriers in pure Ge show strong dependence of their cyclotron resonance spectra on their spatial distribution.
HARP70  "Photothermoelectric Effects in Semiconductors: \( \eta \)- and \( \rho \)-Type Silicon."


- The ability of thermoelectric power measurements to permit a description of carrier-density and phonon-drag variations caused by photoexcitation was tested in 100 \( \Omega \cdot \text{cm} \) \( \eta \)- and \( \rho \)-type silicon. At low temperatures the major effect of photoexcitation is to decrease the phonon-drag contribution to the thermoelectric power by increasing the phonon density in the crystal. At higher temperatures the thermoelectric effect can be used to investigate changes in the electronic contribution due to photoexcitation. An apparently anomalous increase in thermoelectric power with photoexcitation was consistently found in \( \rho \)-type silicon over an intermediate temperature range.

HAYN74  "The COMSAT Non-Reflective Silicon Solar Cell: A Second Generation Improved Cell."


- Photovoltage vs. wavelength show improvement with controlled surface roughness of Si.

HENI56  "Contactless Method for the Estimation of Resistivity and Lifetime of Semiconductors."


- In the processing of semiconducting materials, it is often desirable to estimate the resistivity and bulk lifetime of charge carriers rapidly and without special shaping of the specimens. The device described in this note is designed to accomplish this. Lifetime is measured by illuminating the specimen while it is near the coil and determining the losses introduced by the resulting photoconductivity.
Semiconductor devices with large active areas (power devices, radiation detectors, etc.) have to be manufactured from silicon crystals of homogeneous specific resistance $p$ and excess-carrier lifetime $\tau$ \cite{IGL171, KVST70, LIND73, MAKH69}. The present methods of measuring the homogeneity of these parameters are quite laborious and not always sensitive enough. Here we describe a simple method of simultaneous and continuous determination of $p$ and $\tau$ as well as of their inhomogeneity in high-resistance silicon crystals which is based on measuring photoconductivity at two modulation frequencies.

An analysis is made of the influence of local inhomogeneities on the photoconductivity spectrum and on the spectrum of photoconductivity quenching. GaAs is used to demonstrate that an inhomogeneous distribution of recombination parameters across a sample alters the nature of the photoconductivity spectrum beyond the fundamental absorption edge.

Photovoltage measurements vs. wavelength reveal the controlling importance of carrier recombination in the improved "violet" solar cell devices on the scale of 1000\AA.

The Faraday effect is used for measuring the effective mass of the current carriers in semiconductors and for studying interband transitions. A method is suggested for measuring the angle of rotation of the plane of polarization up to $\pm0.2^\circ$, based on the use of light with variable polarization.
"Free-Exciton Energy Spectrum in GaAs."


- Photoluminescence and reflection at 6471 Å are used to observe the excited states of the free exciton in GaAs, as well as the ground state, up to 40 kG magnetic field.

"Photovoltaic Properties of Anisotropic Relaxation Semiconductors."


- The anomalous photovoltaic effects frequently observed in GaAs and other anisotropic semiconductors are explained in terms of a theory for the influence of nonuniformities on the carrier relaxation.

"Photocurrent and Carrier Distributions Due to Steady Light Absorbed in Finite Thickness."


- The steady-state photocurrent through a layer of photoconducting material is investigated when one of the surfaces is illuminated by a constant light source. The material is assumed to be intrinsic and free of deep traps, light penetration is characterized by an optical absorption coefficient, and bulk recombination is taken into account.

"Energy Relaxation of Photoexcited Hot Electrons in GaAs."


- Photoinduced conductivity permits observation of τ vs. carrier energy in high mobility semiconductors.
"Lifetime of Nonequilibrium Carriers in Single Crystals of Cd$_x$Hg$_{1-x}$Te."


The lifetime was determined by means of measurements of the photoelectromagnetic effect (PME) and the photoconductivity (PC) of n-type specimens with uncompensated donor concentrations of about $10^{15}$ cm$^{-3}$ in the range from 77 to 300K. For the photoelectric measurements we selected the most homogeneous specimen in which there were no parasitic photo-emfs associated with composition or carrier-concentration gradients. The lifetimes found from the separate measurements of the PC and PME and those determined by the method of PC/PME ratios were practically equal, since there is no appreciable capture of nonequilibrium current carriers in the range of temperatures used.

"Study of the Homogeneity of Semiconductor Crystals with the Use of a Moving Light Probe."


A method is proposed for studying semiconductor crystals by way of the bulk photo-emf which arises when a light probe is moved across inhomogeneous portions. If the inhomogeneity is related to a nonuniform distribution of impurities, the relative magnitude and direction of the concentration gradient can be determined.

"Photoluminescence I: Theory."


A major purpose of the present article is to provide an introduction to the theoretical and experimental aspects of the photoluminescence at the research level. In order to maintain self-consistency throughout the article, our development of a subject will often differ in notation and form from the original literature. On the experimental side our purpose is to bring together all of the important independent empirical results and take an overview of the collection of findings to establish what is actually known and what needs additional experimental or theoretical work.
"Photoluminescence measurements on high purity $\eta$-type epitaxial Gallium-Arsenide have shown a correlation between relative intensities of two recombination peaks at 1.515eV and 1.439eV and the compensation ratio deduced from Hall effect measurements. It is possible to study the homogeneity of compensation by scanning the laser excitation.

Simplified Analysis of Electron-Hole Recombination in $\mathrm{Zn}-$ and $\mathrm{O}$-doped GaP."


Photoluminescence from impurity sites — theoretical.

"Spectral Analysis of Photoemissive Yields in GaAs and Related Crystals."


An improved energy-band model for GaAs is reported.

"Luminescence in Silicon-Doped GaAs Grown by Liquid-Phase Epitaxy."


The radiative processes in closely compensated GaAs doped with Si (p-type) and Si+Te ($\eta$-type) have been studied by photoluminescence between 3000 and 770K. These materials were grown by liquid-phase epitaxy. The results strongly suggest that Si introduces two acceptor levels in GaAs with ionization energies of approximately 30 meV and $\sim$100 meV.
"Observations Concerning Radiative Efficiency and Deep-Level Luminescence in \(\eta\)-Type GaAs Prepared by Liquid Phase Epitaxy."


- A study was made of \(\eta\)-type GaAs prepared by liquid-phase epitaxy doped with Si, Ge, Sn, Te and Se by photoluminescence and Te-doped material by transmission-electron microscopy. A broad emission band centered at 1.2 eV (band B) is observed in LPE materials doped with group VI elements.

"Cathodoluminescence of Gallium Arsenide."


- An investigation was made of the influence of the impurity concentration, the density of the incident fast electrons, and the temperature on the spontaneous and coherent luminescence of gallium arsenide. The data obtained indicate that the spontaneous luminescence spectrum has several maxima associated with different transitions: band-band, band-impurity, and impurity-impurity. The intensities of these transitions depend in different ways on the impurity concentration, the degree of compensation of the sample, the excitation level and the temperature.

"Optical Pumping in Nitrogen-Doped GaP."


- Photon absorption resonant with the deep traps formed by N in GaP is used to study impurity density and the charged traps so formed.

"Origin of EPR Signal from Silicon Surfaces."

B. Lemke and D. Haneman, Bull APS 20#12, 1502 (1975).

- EPR signals are traced to microcreecles on silicon surfaces cleaved in UHV at low temperatures at \(g=2.0055\); the lowest spin density corresponded to \(3+2\times10^{12}\text{cm}^{-2}\).
OMEL69  "Equipment for Studying Galvanomagnetic Thermal and Photo Effects in High-Resistance Semiconductors (Exchange of Experience)"

E. M. Omel'yanovskii and N. N. So'rov'ev. Industrial Lab., Vol. 35#2, 1215 (July-December 1969).

- Apparatus has been constructed for measuring resistivity and Hall effect which is also used to study thermal and photoeffects and photoconductance on various semiconductor materials with resistivities up to $10^{-10}$ $\Omega$·cm.

ORLO71  "Use of the Faraday Effect for Investigating the Distribution of Current Carrier Concentrations in n-Type GaAs."

(GaAs) P. B. Orlov, L. I. Kolesnik and Yu. V. Kudin, translated from Zavodskaya Laboratoriya, pp. 440-444, April 1971; Industrial Lab., Vol. 37, 562 (Jan-June 1971).

- The contactless methods which are now more and more extensively used for investigating semiconductor characteristics also include methods by which the concentration of current carriers is measured. Determination of the local concentration would make it possible to examine the distribution of impurities in semiconductor materials. The authors have developed a contactless method of measuring the current carrier concentration in n-type GaAs single crystals by means of the magneto-optic Faraday effect.

ROSS70  "Acceptor Luminescence in High Purity $\eta$-Type GaAs."


- Photoluminescence of epitaxial GaAs in a magnetic field has established the origin of several recombination transitions 20 to 40 meV off the band edge.

SHAH69  "Photoluminescence and Photoconductivity in Undoped Epitaxial GaAs."


- We have measured the photoluminescence and the photoconductivity spectra of pure epitaxial GaAs. The photoluminescence spectra at 20K show 11 sharp peaks (widths 0.1-1.0 meV) between 1.509 and 1.516 eV. The photoconductivity spectra show relatively sharp peaks (widths 12meV) which correspond in energy to some of the emission lines.
Donor-state absorption and photoconductivity spectra of \( \eta \)-type epitaxial GaAs layers with carrier concentrations in the range \( 10^{14}-10^{16}/\text{cm}^3 \) are reported. The essentially effective mass-like behavior of the impurity spectra is confirmed, and ionization energies of 6.08, 5.81, 5.89 and 5.10±0.025 meV are reported for Ge, Si, Se and S donors. The influence of impurity-banding upon the values of \( E_D \) is considered. Central-cell corrections to donor ground-state energies are discussed.

Low temperature measurements of photoluminescence were used to evaluate the progress in materials development. Variation of the impurity type, impurity concentration and method of growth were used to clarify the chemical origin of defects in GaAs.

A luminescence line has been observed at 1.454 ev at 20\(^{\circ}\)K in germanium-doped GaAs. Measurements have been made of the peak energy, intensity and half-width as a function of temperature. It is proposed that the centre responsible for the luminescence is an arsenic vacancy bound to a germanium atom on an arsenic site. Preliminary results indicate that a similar centre is present in silicon-doped GaAs grown from a gallium solution.