I. PHYSICAL ELECTRONICS

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RESEARCH OBJECTIVES

Present objectives lie in three separate areas of physical electronics. The first relates to the properties of semiconductors, the second to thermionic emission problems, and the third to the improvement of instrumentation.

The electrical properties of p-n junctions are being investigated as a function of the temperature and the applied voltage. The observations include a careful determination of the current flow as a function of the voltage and also of the capacity of the junction as a function of the voltage. Analysis of such observations yields interesting data, the interpretation of which will serve to measure the applicability of present theories to the electrical properties of junctions.

In most applications of semiconductor materials, it is desirable to make electric connections with them by means of "ohmic" contacts. The techniques for making ohmic contacts vary considerably and the results are not always successful. Very little data are available on the electrical properties of "ohmic" contacts as a function of current flow, current direction, and temperature. Exploratory studies have been undertaken to investigate these contacts.

Other conduction studies include an investigation of the properties of zinc sulfide and of photoconductive properties of germanium as they are related to surface conditions.

Basic to a better understanding of dispenser cathodes is the development of a method for evaluating them. Preliminary experiments and theory indicate that the best method involves the use of the cathode as a receiver of electrons from a similar cathode used as an emitter. Evaluations by this method are being undertaken. The most important parameter in thermionic studies is temperature. The electron-energy distribution should serve as one of the most accurate methods of determining the effective temperature of an emitter. Instruments and methods are being developed to make this means of temperature determination reliable and accurate.

Not only is it of interest to study the properties of semiconductors but we consider it a worth-while objective to use semiconducting devices in our instrumentation. Two recent developments are: First, the development of a micro-microammeter capable of measuring currents with an accuracy of 1 per cent, or better, over the entire range from 1 ma down to 10^{-14}. This device uses a combination of vacuum tubes and solid-state rectifiers and transistors. Our development is aimed, specifically, toward perfecting the stability of the unit with respect to power-line variations and room-temperature changes. The second instrumental development relates to transistorized power supplies; specifically, to one that will take the place of storage batteries in the operation of potentiometers. Present research indicates that a power supply with a constancy in the fourth or fifth figure can be obtained. As this objective is met, other applications of importance will undoubtedly be investigated and attempts will be made to solve associated problems.

W. B. Nottingham

A. PHYSICAL ELECTRONICS IN THE SOLID STATE

1. Conduction in Zinc Sulfide Single Crystals

This is the final report on the experiments performed on the needle-shaped single crystals of zinc sulfide (ZnS). The details of the experiment and the analysis of results will be found in the author's thesis (1). The techniques of preparing the ZnS crystals and details of the experiment were described in Quarterly Progress Report No. 51, pages 1-2. The needle-shaped crystals have current leads permanently attached to either end. Two other ZnS crystals are used as potential probes part way along the needle length. The potential can be measured with only 200 electrons per second flowing across the crystal-to-crystal contact.

Three ZnS:Cl crystals, and two ZnS:Cu,Cl crystals were studied. In ZnS:Cl, the dark conductivity is dependent upon the voltage: in the forward direction, $i = k_f V^{4.5}$; in the reverse direction, $i = k_r V^{2.5}$. The rectification is not a contact phenomenon, but a distributed property of the crystal. The exponents in the empirical current-voltage relationship vary from crystal to crystal, and in any one crystal they change after exposure to light. As the temperature is increased from room temperature to 150° C, the proportionality factors k_f and k_r increase, but above 150° C there is no increase. At the first application of the voltage, a permanent high-resistance region builds up, over several hours, at the cathode end of the crystal. The crystals are hexagonal, and the c-axis is parallel to the needle axis. The build-up of the high-resistance region proceeds faster in one direction along the c-axis than it does in the opposite direction.

The conduction in ZnS:Cu,Cl crystals obeys Ohm's law at all temperatures between 50° C and 250° C and is the same in both directions. No high-resistance regions and no saturation were observed.

When the crystals were imbedded in a medium of the same index of refraction, examination with a petrographic microscope indicated narrow regions of nonuniformity spaced 20 to 100 μ apart along the needle length. These regions are taken to be regions of extremely high impurity concentration which contribute many electron trapping levels to the forbidden band. The presence of substitutional chlorine in the bulk ZnS lattice creates acceptor levels. In the condition of thermodynamic equilibrium, the acceptor levels are occupied by the donor electrons associated with the chlorine impurity, and the localized trapping levels remain empty. If the acceptor levels outnumber the donors, the conductivity is expected to be p-type. The number of holes in the valence band is calculated as a function of temperature, with the assumption that a fraction $(1-\theta)$ of the acceptor levels is occupied by electrons at 0° K. The hole mobility is estimated on the basis of optical mode scattering. By fitting the resulting expression for the conductivity to the data, the energy of the acceptor level extrapolated to 0° K is found to be 1.24 ± 0.02 ev above the top of the valence band.

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References

1. D. A. Berkowitz, Electrical conduction in zinc sulfide single crystals, Ph.D. Thesis, Department of Physics, M.I.T., December 10, 1958.

2. Characteristics of Semiconductor Junctions

Voltage-current and capacitance measurements on a silicon diffused junction (kindly furnished by the Bell Telephone Laboratories, Incorporated) were made at several temperatures. It has been previously noted (1, 2, 3) that the reverse characteristic of these junctions at lower temperatures shows a pronounced lack of saturation, which has been attributed to recombination within the transition region. At medium reverse voltages, the current thus produced should be proportional to the volume of the transition region, which, in turn, is proportional to the width of the transition region. The capacitance of the junction because of the presence of the carrier-free transition region will be inversely proportional to the width of the region, so that the product of the capacitance and that part of the reverse current resulting from barrier recombination should be a constant as long as the voltage is large compared with the built-in voltage and as long as carrier multiplication is negligible.

The capacitance measurements show that the small-signal capacitance varies as the inverse cube root of the applied voltage, hence the graded junction approximation should be good. If we assume this model, then, from the voltage-current and voltage-capacitance data, we should be able to calculate a number of parameters of the junction (built-in potential, area of junction, width of the transition region as a function of voltage, carrier lifetime, energy level of recombination centers, and so forth). An analysis of data at one temperature (100° C) indicates that such determinations can, indeed, be made; the values of the various parameters are entirely reasonable and in good agreement with other studies (1, 3), and show complete internal consistency. However, a comparison with data obtained at other temperatures indicates that the agreement is not as consistent as could be hoped; in particular, to get agreement with capacitance measurements, the dielectric constant of silicon would have to vary 20 per cent in the range from 30° C to 130° C. This would seem to be a rather large temperature variation; but, since no data seem to be available on the variation of the dielectric constant of silicon, the accuracy of the present model cannot be determined.

Obviously, this work is far from complete, and no complete analysis can be presented.

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References

1. C. T. Sah, R. N. Noyce, and W. Shockley, Proc. IRE 45, 1228 (1957).
2. E. M. Pell and G. M. Roe, J. Appl. Phys. 26, 658 (1955).
3. E. M. Pell and G. M. Roe, J. Appl. Phys. 27, 768 (1956).

3. Surface States on Semiconductors

As we mentioned in Quarterly Progress Report No. 51, page 2, we attempted to create trapping on the surface of an n-type germanium sample by bombarding the gases surrounding the sample with a Tesla coil. This was tried with the residual gas in the evacuated tube and with oxygen introduced from a flask. Most of these attempts in the past had failed.

More recently, we found that a short bombardment of ambient residual gas under low-vacuum conditions (2×10^{-4} mm Hg and higher) increased the photoconductive response – sometimes as much as 20 times. The response was usually linear with light intensity, and sometimes increased more than linearly with light intensity. The transient response was usually immediate, and sometimes with only a very slight rounding of the oscilloscope trace of the response. The increase in response diminished in time after the bombardment. Apparently, the bombardment cleans away some adsorbed layer and thus improves carrier lifetime in the sample.

Bombardment with oxygen resulted in similar changes in the response but created a good amount of rounding of the response trace. This roundness was accompanied by a response that rose less than linearly with light intensity except for the highest illumination levels obtained in the apparatus. Spreading the incident light on a larger section of the sample increased this effect. However, the rise of the transient response was usually slower (and rounder) than the decay, contrary to Gebbie's findings (Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., July 15, 1955, pp. 3-4). When the oxygen was pumped out, the roundness disappeared within a few minutes, and the response again became linear and usually somewhat weaker. This suggests that the roundness is caused by relatively slow charging and somewhat faster discharging (both within milliseconds) of surface states across a high-resistance layer created by bombardment in oxygen, possibly by the adsorption of ozone.

E. Ahilea

B. EXPERIMENTAL TECHNIQUES

1. A Vacuum-Tube-Transistorized Electrometer Millivoltmeter Circuit

A new electrometer circuit has been designed and constructed and is being tested. The circuit consists of three sectionalized units: a basic amplifier unit with an output meter; a detachable input circuit that incorporates the input resistors and feedback network; and a power supply. The detachable input circuit allows several different input and feedback arrangements to be used with one basic amplifier.

Where used as an electrometer the unit will measure 10^{-3} to 10^{-12} amp, full-scale, direct-reading. Currents of less than 10^{-12} amp can be measured by observing the rate of charging of a small condenser.

When it is used as a millivoltmeter, potentials from 10 to 1000 mv, full-scale, can be measured in very high impedances.

The circuit and other details of this unit will be published at a later date.

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2. Transistor-Regulated Power Supply

Further work has been done on the low-voltage-regulated power supply described in Quarterly Progress Report No. 51, page 5. The temperature compensation circuit shown there was difficult to adjust for optimum performance. It has been redesigned and is shown in Fig. I-1. The values given for the resistances provide a fixed output

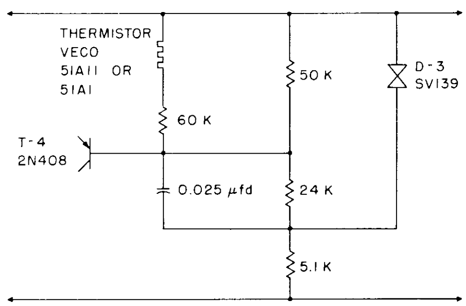

Fig. I-1. Temperature compensation circuit for regulated power supply.

of 25 volts. This will vary slightly from one circuit to another because of variations in the Zener breakdown voltages. Tests were made on a model that incorporates this circuit at an output current of 200 ma. Over a period of 5 days the room temperature was varied between 20° C and 30° C several times. The maximum output variations were ±5 mv from an average value of 25.1700 volts. Variation with changing line voltage amounts to less than ±1.5 mv for ±15-volt changes from the normal 115 volts.

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