I. PHYSICAL ELECTRONICS

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A. PHYSICAL ELECTRONICS IN THE SOLID STATE

1. Conduction in Zinc Sulfide Single Crystals

The difficulties in reproducing current measurements in needle-shaped zinc sulfide (ZnS) single crystals, because of changes in resistance at the contact regions, indicated that potential measurements with the use of probes along the crystal length were necessary. The crystals conduct currents of less than one micro-microampere at the voltages applied; hence high-impedance probes are required. Short needle crystals (2-3 mm in length) of ZnS are used as the probes. They are prepared in the following manner. A short length of 4-mil platinum wire is bent into a U-shape. A 10-mil wire is laid across the legs of the U, which are then wrapped around the wire. The wire is slipped out of the U-frame and replaced with the ZnS probe crystal. The ends of the crystal are painted with Hanovia silver paste, and the 4-mil platinum wire is spot-welded to a 16-mil platinum support rod. The probe assembly is then baked in air at 150° C for 3 hours. Two such probes, and the ZnS crystal that is being tested, are mounted on a 0.5-inch × 0.5-inch Teflon block, and the probe crystals are lowered onto the test crystal – they are held there by the spring force of the 4-mil platinum wire. The test crystal is wrapped at the ends with 1-mil platinum wire, which is relatively flexible, and painted. The 1-mil platinum wire is then spot-welded to 16-mil inch supports that are mounted on the Teflon block. The probe crystals are connected to the two outer terminals of a Teflon SPDT switch. The center connector leads to the insulated quadrants of a Compton quadrant electrometer. The electrometer is operated at a sensitivity of 5000 mm/volt, and is used to detect a deviation from the estimated value of the probed potential. The system will detect the voltage distribution along the ZnS crystal with an accuracy of ±.25 volt in 100, and draws a current of less than 10^{-15} amp across the physical contact between the ZnS test crystal and the ZnS probe crystal.

On a ZnS;Cl test crystal, the observed current versus probed voltage (V_{12}) characteristic was strongly nonlinear. At five temperatures: 50°, 100°, 150°, 200°, and 250° C, the i-V curve obeyed the power law $i = kV_{12}^{4.5}$, within experimental error, for applied voltages up to 300 volts – the limit of the measurement. The characteristic for voltages applied in the opposite direction was different. At 200° C, $i' = k' V_{21}^{2.3}$. Exposure to room light between measurements alters the exponents, but continuous measurements made in the dark, with each run preceded by a temperature cycling to 250° C at zero applied voltage for 1 hour, were reproducible.

From the i-V characteristics, the conductance at constant voltage was determined for the five temperatures, and the logarithm of the conductance was plotted against the reciprocal absolute temperature. The slope at low temperature implied an activation energy of 0.25 ev. At high temperatures, the conductance became constant.

Probe measurements on two test crystals indicated that at the first application of the voltage, most of it appeared at the cathode end of the crystal; in later measurements the voltage appeared at the same end regardless of whether or not it was the cathode. A long crystal was broken into halves, labeled "A" and "B". When 120 volts was applied to A at 150°, within a few minutes, most of the 120 volts was at the cathode end. For B, under the same electrical conditions but with B oriented antiparallel to A, the voltage still appeared at the cathode end, but took approximately 10 times longer.

The author is indebted to Dr. R. C. L. Slater for the X-ray examination of a sample of the ZnS;Cl crystals, which showed a hexagonal wurtzite structure of correct spacing with the hexagonal axis along the needle axis. It has been reported (1) that ZnS single crystals of this form are directional. Indeed, in our experiments, the crystal behavior was different in one direction from that in the opposite direction.

In order to understand the way in which the empirical activation energy is related to the impurity levels in the forbidden band, it is necessary to know the concentration of carriers. An expression that is exact, on the basis of the Fermi statistics, for this concentration for an n-type semiconductor with a single donor level has been given by Professor Nottingham (2). The same type of calculation has been made for the case in which a single trapping level of various depths and concentrations is present also.

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References

1. G. Cheroff and S. P. Keller, Phys. Rev. 111, 98 (1958).
2. W. B. Nottingham, Thermionic emission, Handbuch der Physik, Vol. 21 (Springer Verlag, Berlin-Göttingen-Heidelberg, 1956), p. 1; Technical Report 321, Research Laboratory of Electronics, M.I.T., Dec. 10, 1956.

2. Surface States on Semiconductors

The purpose of this experiment is to study the correlation between changes in the surface-trap density of germanium and the changes in the contact potential of germanium. Both of these changes are caused by changes in the gases surrounding the germanium sample.

Since the effects that we believe are caused by trapping of minority carriers could not be reproduced in the experimental tube that was being used in this research, we decided to try to reproduce them in the demountable brass tube which Gebbie originally used in his investigation of these effects (1). Several experiments were made with samples cut from crystal 505, which was grown in Lincoln Laboratory. This was an

18 ohm-cm, undoped, n-type germanium crystal from which most of Gebbie's samples were cut. The rise and decay of photoconductivity were instantaneous in all but one case in which the rise and decay were more rounded, asymptotic, and slightly asymmetric; in all cases, however, the photoconductivity was linear with light intensity. (We believe that the rounded and asymmetric rise and decay and nonlinearity of the photoconductivity as a function of light intensity are caused by trapping.) The response was very good in almost all cases, which indicated a low recombination rate, and the difference between the best and the worst cases was not of more than one order of magnitude.

Another sample, which was cut from a different crystal with specifications similar to X505, was tried. This trial produced the desired effects once, with the response curve analyzed into a linear and a saturating component. Bombarding the sample with a Tesla coil and residual gas in the vacuum system increased the saturation value approximately 22 per cent, with a negligible change in the linear portion. Bombarding with some oxygen which was introduced from a flask increased the saturation value 65 per cent above the original value, with an apparent 10 per cent decrease in the linear component. After re-etching, the effect was gone and could not be reproduced.

All samples had four wires tin-soldered to them by Nokorode flux, and the soldered connections were protected by nail polish from the CP-4 etch. The samples were etched before each installation in the tube.

E. Ahilea

References

1. H. A. Gebbie and E. Ahilea, Surface studies on semiconductors, Quarterly Progress Report, Research Laboratory of Electronics, M.I.T., July 15, 1955, pp. 3-4.

3. Characteristics of Semiconductor Junctions

The data recently taken by Mr. Bruce Hayworth, of this laboratory, on one of the junctions (JA 357) previously studied (Quarterly Progress Report, July 15, 1958, p. 2) have been analyzed. On the basis of the simplest diffusion-current analysis (1), the saturation current I_s should be given by

$$I_s = A\left(\frac{kTq\,\mu_p}{\tau_p}\right)^{1/2} \frac{N_c N_v}{N_d} \exp(-W_G/kT)$$

where A is the junction area, k is Boltzmann's constant, q is the value of the electronic charge, μ_p is the drift mobility of holes in the n-type material, τ_p is the hole lifetime in the n-type material, N_c and N_v are the effective densities of states in the conduction and valence bands, respectively, N_d is the donor concentration in the n-type material, and W_G is the width of the forbidden gap. With the use of voltage-current data for different temperatures in connection with a master curve, the saturation current can be determined as a function of temperature with an accuracy much greater than that previously reported. Since good values for all quantities (2) except lifetime are known, a measurement of lifetime would allow a complete comparison of theory with experiment. Unfortunately, no equipment is available for making the lifetime measurements, and so a complete comparison is not possible, but lifetimes calculated point by point from the data are in good agreement with previous studies (3). It is possible that lifetimes are not measurable with the same accuracy as the saturation-current data, but an attempt will be made to do so.

The search for a low-voltage high-impedance null-detector has continued with present emphasis on a photoconductive chopper. The best performance so far has been with a cadmium selenide cell illuminated with pulses from a neon lamp. By using two such cells, illuminated alternately in a circuit that, in effect, switches the amplifier input from the voltage that is being measured to ground, an input impedance of 10 megohms with a noise level of approximately 10 microvolts was achieved. The zero stability of this unit is sufficiently good so that no zero compensation is needed.

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References

1. W. Shockley, Bell System Tech. J. 28, 435 (1949).
2. E. M. Conwell, Proc. IRE 46, 1281 (1958).
3. E. M. Pell, J. Appl. Phys. 26, 658 (1955).

B. ELECTRON EMISSION

1. The Thermionic Diode as a Heat-to-Electric-Power Transducer

Recent work (1) on the application of the thermionic diode as a transducer has made it seem worth while to examine this problem in the light of the theories presented in "Thermionic Emission" (2). The results of this study are embodied in an article that will be published in the Journal of Applied Physics, in which the following facts are brought out.

It is shown that the high-vacuum thermionic diode is capable of converting heat to electric power. For this purpose, a low-work-function collector, small spacing, and sufficient temperature difference between the emitter and the collector are necessary. A detailed understanding of both thermionic emission and space-charge phenomena are needed for evaluating the effectiveness of this transducer. With V_R defined as the critical bias potential that gives zero potential gradient at the collector, the maximum available power is given by the relation $3.7 \times 10^{-6} V_T^{1/2} \left(V_R^2/w^2\right)$ watts/m^2. Here, V_T is the voltage equivalent of the temperature T/11,600. In the range of emitter temperature from 1200° K to 1700° K, the most optimistic conversion efficiency lies between 3 and 4 per cent for a diode of 0.001-inch spacing. With a suitable choice of emitter inhomogeneity, the introduction of cesium vapor should improve the efficiency of this device.

W. B. Nottingham

References

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2. W. B. Nottingham, Thermionic emission, Handbuch der Physik, Vol. 21 (Springer Verlag, Berlin-Göttingen-Heidelberg, 1956), p. 1; Technical Report 321, Research Laboratory of Electronics, M.I.T., Dec. 10, 1956.

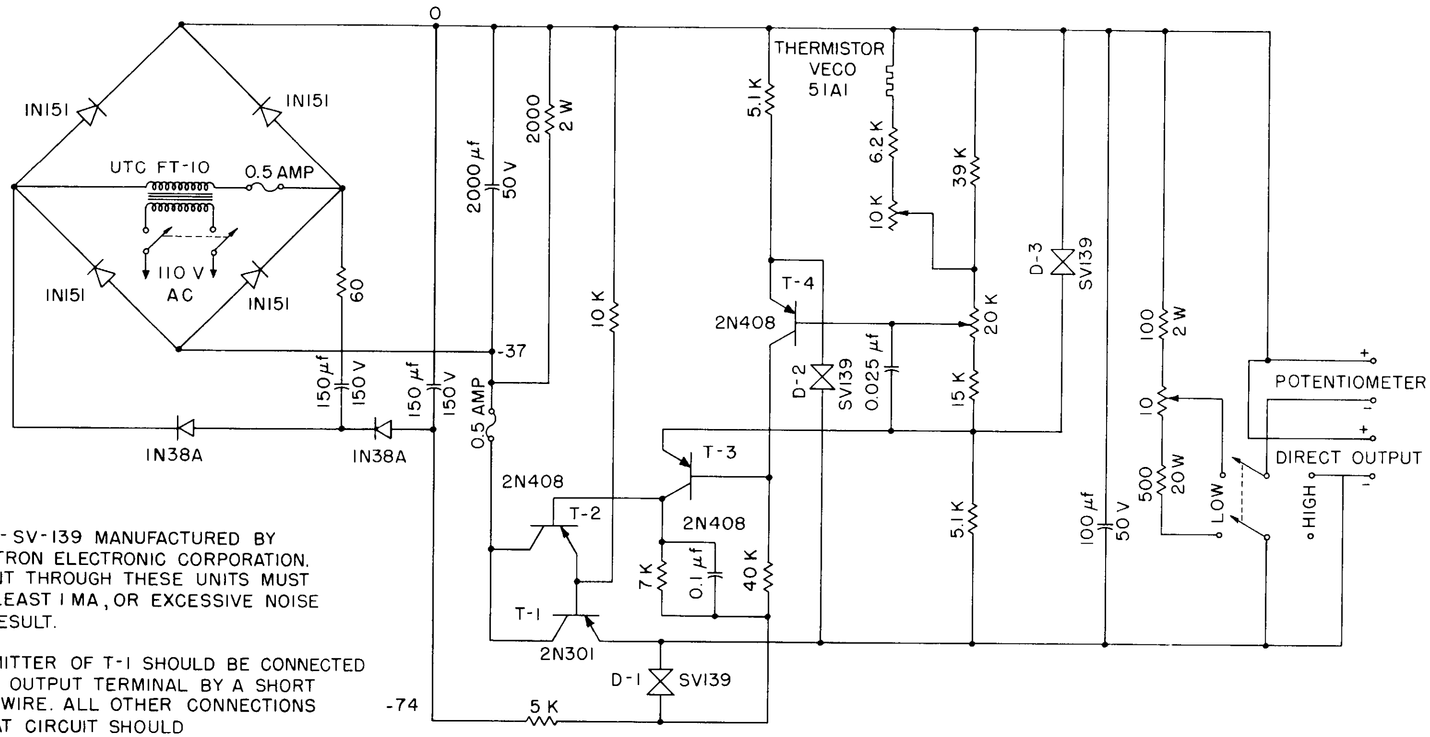
C. EXPERIMENTAL TECHNIQUES

1. Transistor-Regulated Power Supply

A low-voltage regulated power supply has been developed with the use of transistorized circuitry. This power supply can be used to replace storage and dry batteries as a source of power for operating precision potentiometers, heating filaments for thermionic emission studies, operating transistor circuits, and other applications in which an exceedingly well-regulated low-voltage power source is required.

The circuit shown in Fig. I-1 will supply 1/2 amp at 21-30 volts. Two Zener avalanche diodes are used as reference elements. The output voltage is equal to the voltage across D-2 plus the part of the voltage across D-3 that appears across the upper part of the voltage divider. Any decrease in output voltage will cause an increase in the emitter-to-base voltage of T-4, which is a pnp transistor. T-3 and T-4 form a high-gain dc amplifier for driving T-2. T-2 is an emitter follower that provides sufficient current amplification to drive the power transistor T-1 at high output currents. The negative collector bias for T-3 and T-4 is provided by a voltage doubler and is regulated by D-1.

A thermistor in the voltage-divider circuit provides a negative temperature coefficient to compensate for the positive temperature coefficient of the Zener diodes and T-4. The amount of compensation can be adjusted by R-4 so that the output voltage varies less than 1.0 millivolt per degree centigrade change



NOTES:

1. D-1,2,3-SV-139 MANUFACTURED BY TRANSITRON ELECTRONIC CORPORATION. CURRENT THROUGH THESE UNITS MUST BE AT LEAST 1 MA, OR EXCESSIVE NOISE WILL RESULT.

2. THE EMITTER OF T-1 SHOULD BE CONNECTED TO THE OUTPUT TERMINAL BY A SHORT HEAVY WIRE. ALL OTHER CONNECTIONS TO THAT CIRCUIT SHOULD BE MADE THERE.

Fig. I-1. Transistor-regulated power supply.

in temperature from 20° C to 35° C.

The variation in output voltage from zero to full load is 0.005 volt, which corresponds to an output resistance of 0.01 ohm. The output also varies less than 0.0001 volt per volt change in ac line voltage from 90-125 volts. Ripple and noise are less than 200 microvolts or 0.001 per cent. The voltage divider and switch across the output provide a 2-volt output for operating a Leeds and Northrup Type K potentiometer.

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