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AUTOMATED DATA COLLECTION SYSTEM APPLIED TO HALL EFFECT AND RESISTIVITY MEASUREMENTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A description of the instrumentation and theory of operation of a fully programmable, automated Hall effect and resistivity apparatus is presented. The apparatus has the capability of controlling all operational conditions over a wide range of temperatures and logging data in the form of both typewritten copy and computer-compatible punched paper tape.

Application of the system for measuring both thin film and bulk samples of cadmium sulfide and bulk samples of n-type and p-type silicon in the temperature region between 4.2° and 400° K is discussed. Also discussed are a simple, yet highly reliable, technique for obtaining ohmic contacts to the samples, the systematic procedure followed for each measurement run, the data program and computer recording format, and samples of the computer results.

Extension of the system to include measurement of materials of high resistivity was achieved by operating a high-input-impedance electrometer between the sample leads and the input scanner. A sample holder was designed to accept either thin-film samples on substrates up to 1-inch (2.54 cm) square or bridge-shaped bulk samples. A complete Dewar system was assembled for controlling the temperature and sample environment at temperatures between 4.2° and 400° K. The system accuracy and specifically the accuracy of the reduced Hall effect and resistivity measurements are discussed. Calibration procedures for the thermocouples and gaussmeter are outlined.

INTRODUCTION

This report describes both the construction and application of a function-programmed, automatic data-collection system designed primarily to (1) control an experiment automatically, (2) record data, and (3) place data in a form acceptable for computer processing. Up to the present time, most of the standard commercial automatic data-collection systems available have not been provided with the means of programming and controlling an experiment or test in addition to their normal functions, items (2) and (3). Although the primary purpose to automate was directed to Hall effect and resistivity measurements, versatility was kept in mind throughout the design and construction phases of this work to permit the resulting system to be adaptable to other experiments. Similar automatic Hall effect systems have been described by Putley (ref. 1) and another such system was constructed by Whitsett (private communication with C. R. Whitsett of McDonnell Aircraft Corporation, St. Louis, Mo.).

By using available components of commercial data-logging systems as a basis, additional components were designed and constructed at the Lewis Research Center to complete a fully function-programmable, automated Hall effect and resistivity apparatus (fig. 1) capable of controlling all operational conditions and logging data on both crystalline and thin-film samples over a wide range of temperature. Most measurements obtained to date have fallen into the temperature range between 4.2° and 400° K because

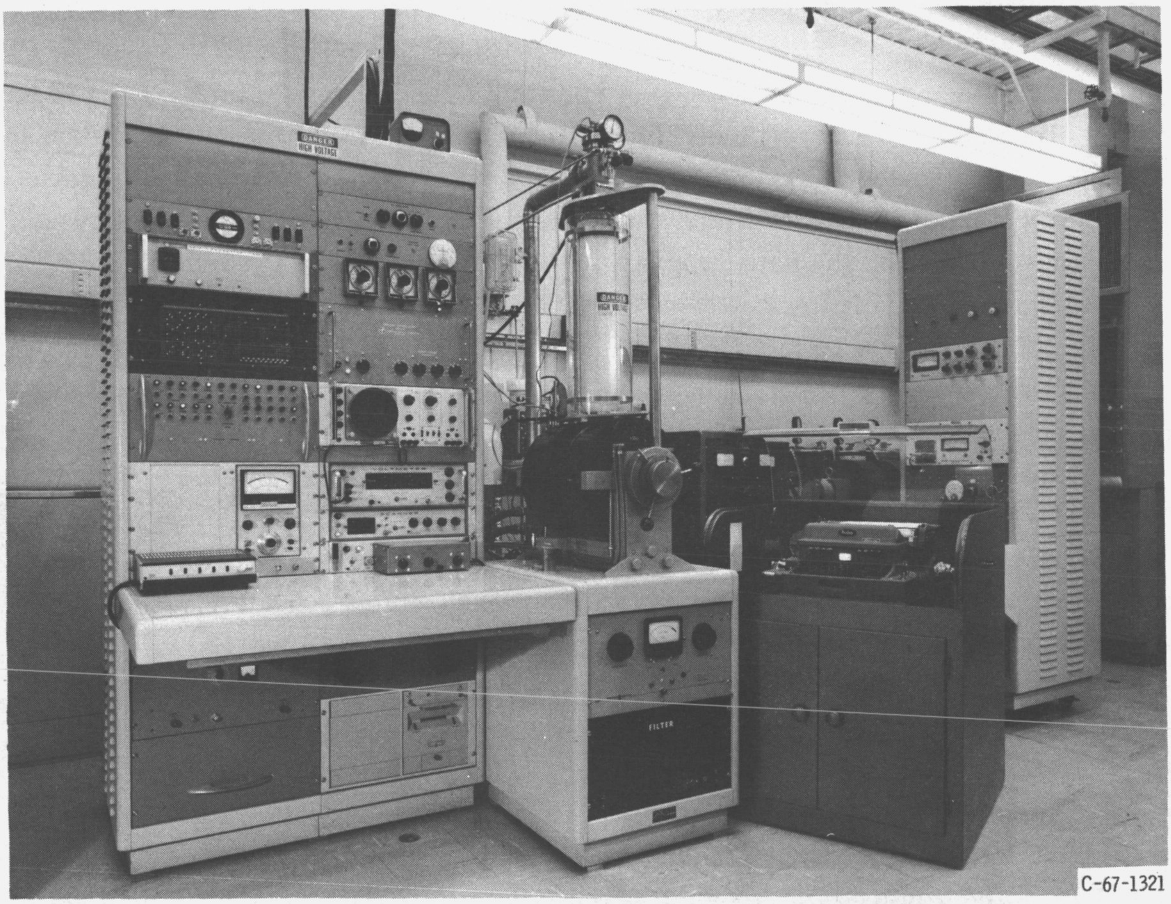


Figure 1. - Automated Hall effect and resistivity apparatus.

of the Dewar system and sample holders initially chosen. On the cadmium sulfide and silicon crystals tested, the system has operated fully automatically and unattended for measurements between 300° and 80° K. Below 80° K some manual attention may be necessary to maintain reasonable accuracy. The amount of manual attention required depends on two factors, the rate of change of the parameter being measured and the source impedance of the input being measured. Additional points covered include extensions of the initially designed system, sample contact problems and solutions, and the data-recording format used.

APPARATUS

Instrumentation

A block diagram of the automatic Hall effect and resistivity measuring system is shown in figure 2. The primary components of the system include a 50-step-shielded

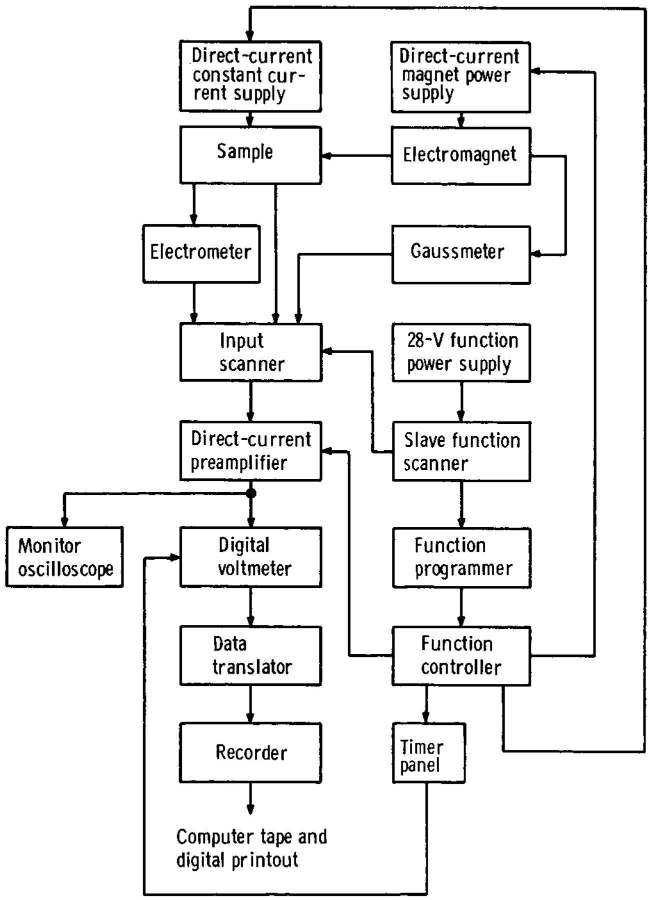


Figure 2. - Block diagram of function-programmable, automated Hall effect and resistivity measuring system.

2-wire input scanner, a timer panel, a 50-step function scanner, a function control relay chassis with manual or automatic switching modes, a 50-step function programmer, a direct-current preamplifier, an oscilloscope signal monitor, a null-balance type 4-digit-autoranging digital voltmeter, a data translator, and a recorder that provides both type-written copy and computer-compatible punched paper tape outputs. A 0.01 to 230-milliampere constant current supply normally provides the current to the sample. The input scanner, direct-current preamplifier, digital voltmeter, magnet power supply, and recorder used in this system were commercial components that required minor modification. The data translator, constant current supply, and oscilloscope were commercial components that did not require further modifications. The slave function scanner, function programmer, function controller, Gaussmeter power supply, timer panel, and 28-volt-direct-current power supply were designed and constructed at Lewis, with the exception of the function programmer board, which was constructed by a contractor. Auxiliary equipment frequently used with the system includes an electrometer with an input impedance of 10^{14} ohms and a low-noise battery power supply used to provide sample current for high resistivity materials.

Sample Holder

The sample holder, shown in figure 3, was designed to accept either thin-film samples on substrates up to 1-inch (2.54 cm) square or bridge-shaped bulk samples.

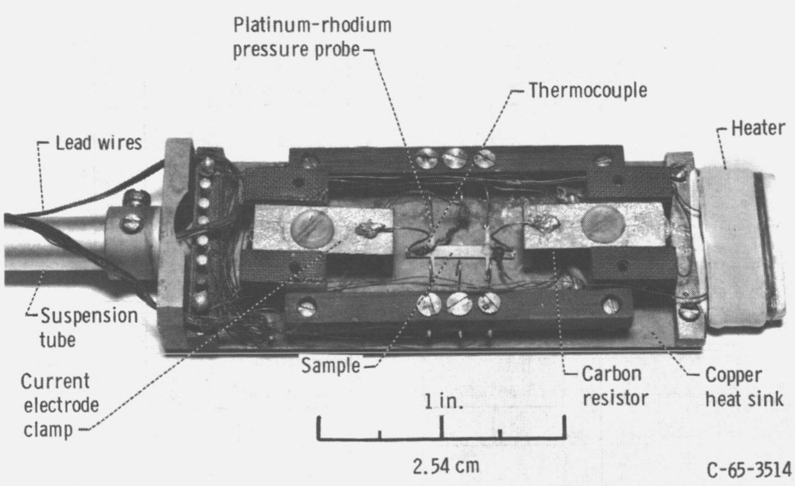


Figure 3. - Sample holder.

Eight 0.010-inch-diameter (0.0254 cm) platinum-rhodium wire pressure probes were provided for making electrical contact with the sample. These probes are easily bent to contact almost any shape of sample that may be placed in the holder. However, the

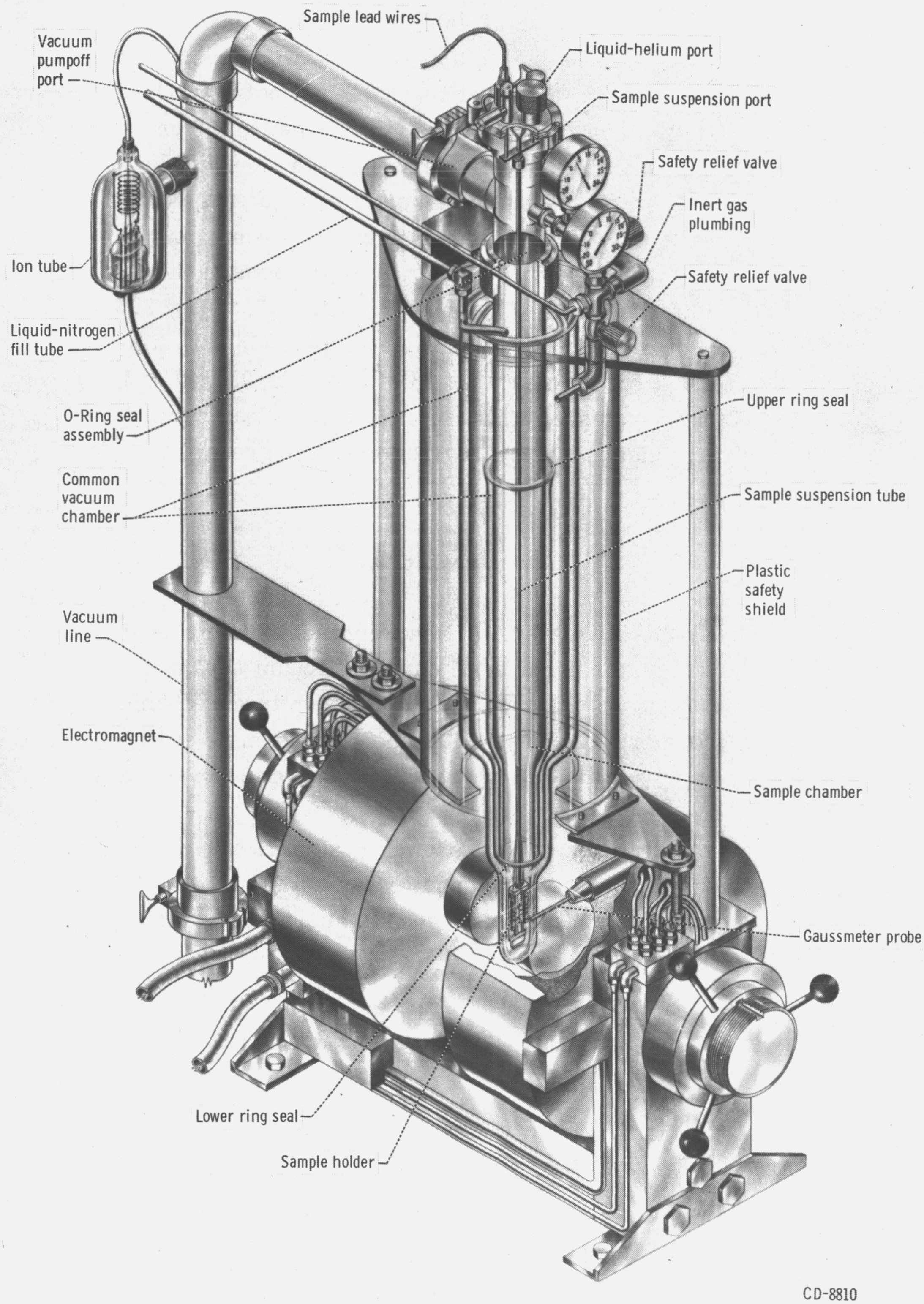


Figure 4. - Dewar system and electromagnet arrangement.

author standardized on a six-ear bridge-shaped thin-film sample and three convenient sizes of four-ear bridge-shaped bulk samples. Thermocouple grade, polytetrafluoroethylene-insulated, 0.003-inch-diameter (0.00762 cm) solid copper wire was used for leads between the probes and the measuring apparatus. Two copper-constantan thermocouples fabricated from 0.003-inch-diameter (0.00762 cm) polytetrafluoroethylene-covered wire are shown in figure 3. The two 1/4-inch-wide (0.635 cm) screw-adjustable clamps that appear at each end of the sample serve as both current electrodes and holding clamps for thin-film samples. The sample holder is also equipped with a small heater located at the base of the holder and a permanently mounted carbon resistor for low-temperature calibration purposes. The overall dimensions of the sample holder with the heater assembly attached is 2.9 by 1.0 by 0.4 inch (7.366 by 2.54 by 1.016 cm). The holder is attached to the end of a 1/4-inch-diameter (0.635 cm) thin-wall stainless-steel tube suspension assembly that measures 43 inches (109.22 cm) in length and is shown in place in the Dewar system in figure 4. All sample lead wires in the measuring circuit are electrically shielded and normally isolated from ground.

Dewar System

As shown in figure 4, the silvered glass Dewar presently being used is a double chamber system where a common permanently sealed vacuum separates both the sample chamber from the liquid-nitrogen chamber and the liquid-nitrogen chamber from the room-temperature environment. A vacuum pumpoff port, sample suspension port, inert gas plumbing, and appropriate safety valves are shown in the O-ring sealed superstructure at the top of the Dewar.

Also shown in figure 4 at the base of the Dewar system is a 4-inch (10.16 cm) water-cooled electromagnet used to provide the magnetic flux for the Hall work. A Hall effect gaussmeter probe is permanently mounted between the pole pieces for measuring the magnetic field.

PROCEDURE

Theory of Operation

The lead wires of the sample holder are wired to a terminal board that provides up to fifty 2-wire shielded inputs to the input scanner. The input scanner selects the appropriate signal pairs for measurement and connects them to the preamplifier input. At the instant that a particular pair of measuring leads are selected by the input scanner, the function programmer simultaneously switches all the functions that are programmed for that particular step.

The function scanner precisely tracks the input scanner and distributes the output of the 28-volt-direct-current power supply to energize the appropriate relays in the function control circuit. The selection of which relays will be energized or what functions will be switched prior to the measurement of a particular input is determined by the function-programmer board. This pin-board arrangement permits the programming capacity of either the "on" or "off" mode of 10 functions for each of the 50 steps or inputs that can be selected by the input scanner. For this particular Hall effect and resistivity program, the function programmer automatically controls the following functions that would normally be controlled by an operator working with the system in the manual mode of operation: the magnetic field on-off switching and its polarity, the sample current on-off switching and its polarity, three delay timers for inserting time delays prior to particular voltage measurements (one of which can be used to control data-cycle frequency), and preamplifier control. Each set of relay contacts in the function-control circuit are terminated in both ribbon connectors and terminal strips. The terminal strips provide easy access to programmed relay contacts when it is desired to switch functions other than those associated with the Hall effect and resistivity program.

Since the preamplifier is fully controlled by the function programmer when the system is operating in the automatic mode, the input signal is routed through the preamplifier, if required, and the appropriate programmed gain is chosen. The preamplifier can be switched in or out and gains of 10, 100, or 1000 programmed. The amplified signal is then routed to the autoranging digital voltmeter where it is measured, displayed on the front panel digital readout, and outputed to the data translator. The data translator takes the voltmeter reading along with other 10-line parallel information, which includes the input scanner channel identification, voltage exponent polarity, voltage exponent (decimal point location), and voltage polarity, serializes it to conform to the data word format, converts it to the 1-2-4-8 BCD code (binary coded decimal) and outputs the information to the recorder. At the recorder, the data are punched on 1-inch wide computer-compatible paper tape and are also printed on paper in the form of a decimal data word consisting of 8 digits, a polarity symbol, and a space or carriage return.

For each temperature cycle of data, the preceding sequence of operations continues until all 19 voltages, that are required for this particular Hall effect and resistivity program, are measured and recorded. Once a full temperature cycle is recorded, the input scanner automatically resets to the first input. A timer is programmed in on the first step of the cycle to control the frequency of the data cycles. When the timer times out, the two scanners again regain control of the system and allow a new temperature cycle of data to be recorded.

Sample Temperature and Environment Control

The manner in which the temperature of the sample is varied between room temperature and liquid-helium temperature requires the run to be broken initially into two parts. The first part of the run is from room temperature to liquid-nitrogen temperature. Two important points must be observed: (1) dry nitrogen or helium gas must be in the sample chamber, and (2) no water may be present at the lower ring seal of the liquid-nitrogen chamber. Two slits in the silvered walls of the Dewar permit one to observe when the chamber is sufficiently dry for use. The chamber is then filled with liquid nitrogen to a point approximately 3 inches (7.62 cm) above the upper ring seal of the vacuum chamber that separates the sample chamber from the liquid-nitrogen chamber (shown in fig. 4, p. 5). The liquid nitrogen is thus placed in thermal contact with the nitrogen gas in the sample chamber through a single glass wall that separates the two chambers at this point. The sample is allowed to free-cool by gas convection, and data are recorded at specific time intervals until the sample temperature drops to approximately 90° K. Since approximately 75 seconds are required to record one full temperature cycle of data, it is desirable to maintain a reasonably slow cooling rate as a means of keeping the temperature measurement errors to a minimum even though the temperatures calculated are averaged over the time span of a cycle. The temperature change is normally within the range of 0.5° to 1.0° K over the period of one measurement cycle. By this free-cooling method, approximately 5 to 7 hours are required to reach 90° K. The system is usually refilled with liquid nitrogen and left overnight in this condition before the second part of the run is recorded.

To initiate the second part of the run, the liquid-nitrogen level is brought up to a point just below the upper ring seal, and the nitrogen gas, if used, is pumped out of the sample chamber with the forepump. Helium gas is then introduced into the system until atmospheric pressure is reached. A small amount of liquid helium is then transferred into the sample chamber. Generally, prior to commencing with the second part of the run, it is necessary to reset the sample current and reprogram preamplifier gains to accommodate, in many instances, several orders of magnitude change in the electrical properties of the material observed at extremely low temperatures. After the functions necessary are programmed, the liquid helium in the Dewar is either forced or allowed to boil away freely. Following this procedure, the data are automatically recorded as the system free-warms to a temperature point that overlaps the data recorded during the cooling cycle. This data overlap region is used as a means of determining if any hysteresis effects exist between the cooling cycle and the warming cycle data.

The lowest temperature at which meaningful measurements can be obtained on semiconductors with this system is determined by the source resistance of the sample and the rate of change of the particular property being measured as a function of temperature.

For example, the electrical resistivity of a sample of boron-doped p-type silicon increases from 9.3 ohm-centimeter at 298° K to 3.4×10^6 ohm-centimeter at 23° K. This increase means that the input-source impedance of the sample probes being measured approaches, or even exceeds, the input impedance of the measuring instrument. One-percent data can only be obtained to the point where the input impedance of the source remains 2 orders of magnitude below that of the measuring instrument. On high resistivity materials at low temperatures, then, it is necessary to use extremely high-input-impedance voltmeters. An electrometer with an input impedance of 10^{14} ohms, used between the signal pair to be measured and the input scanner, significantly extends the useful range of the system. The use of this instrument, however, requires two additional liquid-helium runs; the first is used to extend the resistivity data and the second, the Hall data. These two runs can be accomplished in 1 day, however, thus bringing the total running time to 3 days, which includes four distinct temperature runs per sample. The two additional liquid helium runs could be reduced to one with the addition of another electrometer.

Hall Effect and Resistivity Data Program

Several thermoelectric and thermomagnetic effects can accompany the Hall effect in a material and, consequently, introduce errors in the Hall voltage measurement if certain precautions are not taken. A detailed discussion of these problems and the procedures to eliminate them have been published by Harman (ref. 2). In selecting a program for the automatic system, every attempt was made to choose a general program that would yield accurate Hall effect and resistivity data, regardless of the type of material measured. Finally, a three-phase program was adopted where either the Hall effect or resistivity could be measured and processed independently or combined into one program. In table I the data program used for each temperature cycle of data is shown for the combined program and its component parts. The scanner can be programmed to scan channels 01 to 08 for resistivity only; channels 07 to 19 for Hall effect only; or channels 01 to 19 for the combined program. (All symbols are defined in the appendix.) The computer program was written to accept and process the data in any one of these three forms.

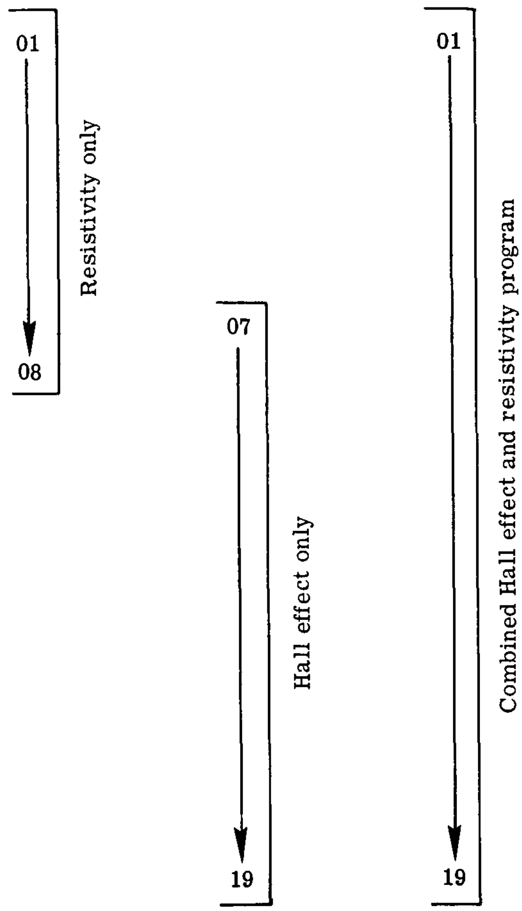
Measurements on High Resistivity Materials

The fully automated system generally limits materials studied to those of low to moderate resistivities because of the input impedance of the preamplifier and digital

TABLE I. - HALL EFFECT AND RESISTIVITY DATA PROGRAM

FOR SINGLE TEMPERATURE CYCLE

Scanner channel	Data, V
01	$V_{T,A1}$
02	$V_{T,B1}$
03	$V_{I+,R}$
04	V_{R+}
05	V_{R-}
06	$V_{I-,R}$
07	$V_{T,A2}$
08	$V_{T,B2}$
09	V_{H+}
10	$V_{I+,H}$
11	$V_{H+,I+}$
12	$V_{H+,I-}$
13	$V_{I,H}$
14	$V_{H-,I+}$
15	$V_{H-,I-}$
16	$V_{I-,H}$
17	V_{H-}
18	$V_{T,A3}$
19	$V_{T,B3}$



voltmeter. The input impedances of the preamplifier and digital voltmeters are 100 and 10 megohms, respectively, which limits the source resistances to 1 megohm and 100 kilohms, respectively, if loading errors are to be held to a 1-percent maximum. By operating a high-input-impedance electrometer (10^{14} ohms) ahead of either the preamplifier or digital voltmeter, the useful measurement range of the system was extended to include moderately high resistivity materials. Figure 5, for example, shows how the use of the electrometer permitted a 50-percent extension of the plot of logarithmic resistivity $\ln \rho$ against reciprocal temperature for a single crystal sample of p-type silicon. At source resistances greater than 6.6×10^{5} ohms, loading errors become unbearable as $1/T$ increases when the digital voltmeter is used alone. If the digital voltmeter alone were used for measurements at the point where a source resistance of 2.4×10^{9} ohms is indicated, an error of -62 percent in the measurement would have

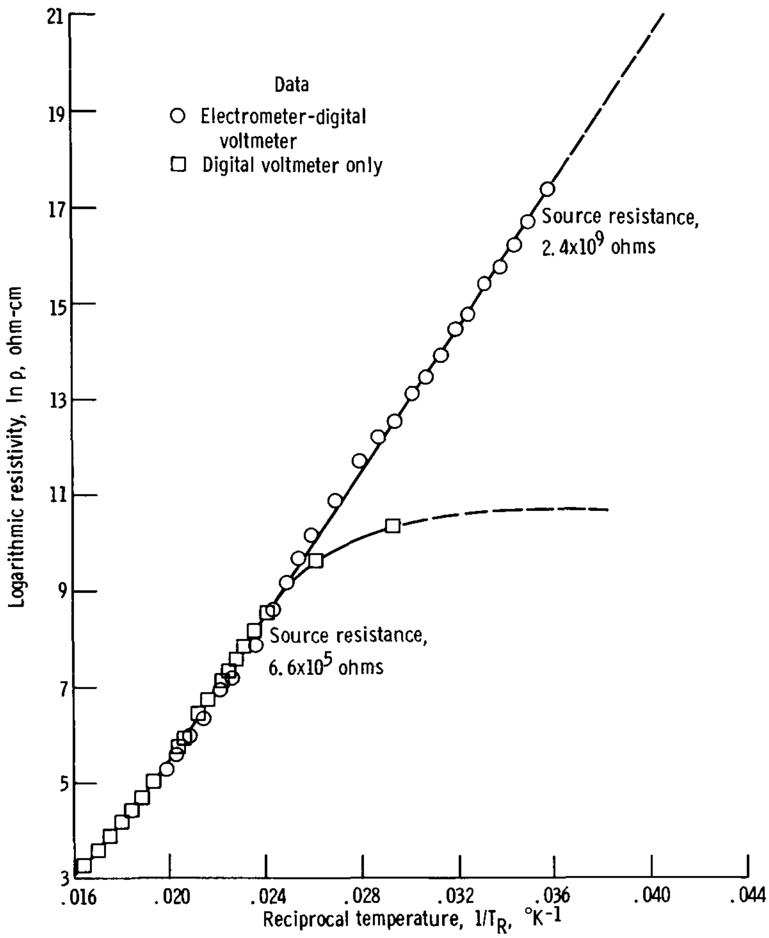


Figure 5. - Extension of measurements using electrometer with system.

occurred. The absolute accuracy of the measuring system does suffer slightly, however, when the electrometer is used in front of the preamplifier or digital voltmeter. It is obvious from figure 5 that this slight loss in absolute accuracy is negligible when compared with the gains achieved through the use of the electrometer. Comparable gains are also realized in the acquisition of the Hall data. For 1-percent data, it is estimated that the present system (including the electrometer) has a practical limit of input source resistance of 10^{10} ohms. This limit is imposed by the fact that the leakage resistance between the lead wires of the sample probe circuitry is of the order of 10^{12} ohms.

DATA RECORDING FORMAT

Table II illustrates the data-recording format used, which includes predata, sample data, and a breakdown of the sample data word. The first four words are predata words that transmit instructive information to the computer as to how the data are to be proc-

TABLE II. - RECORDING FORMAT

Typical data word

0	1	2	3	+	1	4	2	5	

Character	Meaning
(blank)	Space or carriage return
5	Data (units)
2	Data (tens)
4	Data (hundreds)
1	Data (thousands)
+	Data polarity symbol
3	Exponent (decimal point location)
2	Control character (exponent polarity)
1	Scanner channel identification (units)
0	Scanner channel identification (tens)

Typical predata words

0180 - 2601		0200 - 0001		0300 - 0001		0400 - 0901	
Beginning of record	Facility identification	Cyclic mode control	Data program number	Predata word number	Data run number	Number of predata words	Cycle key

Number of predata words and Cycle key: Computer control information

$$\underbrace{0523+0054}_{w}\ \underbrace{0623+0113}_{t}\ \underbrace{0723+0229}_{l}\ \underbrace{0822+0100}_{g}\ \underbrace{0923+1000}_{R_s}$$

Calculation constants used in the data reduction program
(floating point word format identical to data word format)

cessed. The following five words are also predata words in which calculation constants are entered. These constants, beginning with predata word number 5 are sample width, sample thickness, resistivity probe spacing, a geometric factor that relates the sample length to width ratio, and the value of the standard resistor used for sample current calculations. All nine predata words are manually punched on the data tape. Any significant errors that may have been introduced during the recording of experimental data are usually corrected by an operator at the recorder prior to transmittal of the data tape to the computing facility. The last five words of predata and all data words are recorded in "floating point" form and in the same format. The data word contains two input-scanner channel identification characters, one exponent polarity or error code character, one exponent character, one data polarity symbol, four characters of data, and one end-of-word character (space or carriage return). The system presently has the capacity to record four significant figures of voltage ranging from 1.000×10^{-3} to

9.999×10^3; however, numbers ranging from 1.000×10^{-9} to 9.999×10^9 are possible with this format if needed.

OHMIC CONTACTS

Ohmic contacts have been obtained on almost all the materials measured to date with the apparatus through soldering or capacitive-discharge spark-welding techniques. The spark welder circuit, shown in figure 6, is basically a bank of capacitors, ranging from 0.001 to 50 microfarads, wired to a selector switch. A capacitor is selected and charged by a variable 0- to 300-volt direct-current voltage source and then discharged through the sample contact. A test switch is provided to switch the sample contact leads to a test instrument to check the contact after each discharge pulse. The type of metal required to form nonrectifying alloy contacts to the sample is dictated by the type of semiconductor material to which contact must be made. Rather than change the pressure probes in the sample holder each time that a different contacting metal was required, a simple technique was devised where small metal foil disks of the metal to be alloyed are sandwiched between the pressure probe and the sample at each contact point. By placing a metal electrode of the same material in contact with the sample at a point

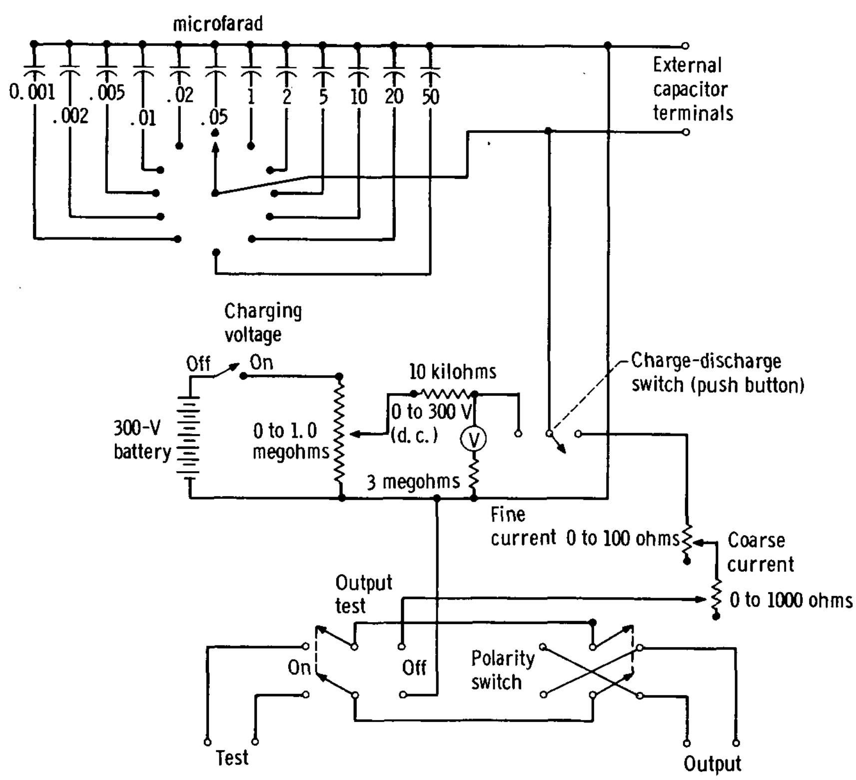


Figure 6. - Spark welder circuit.

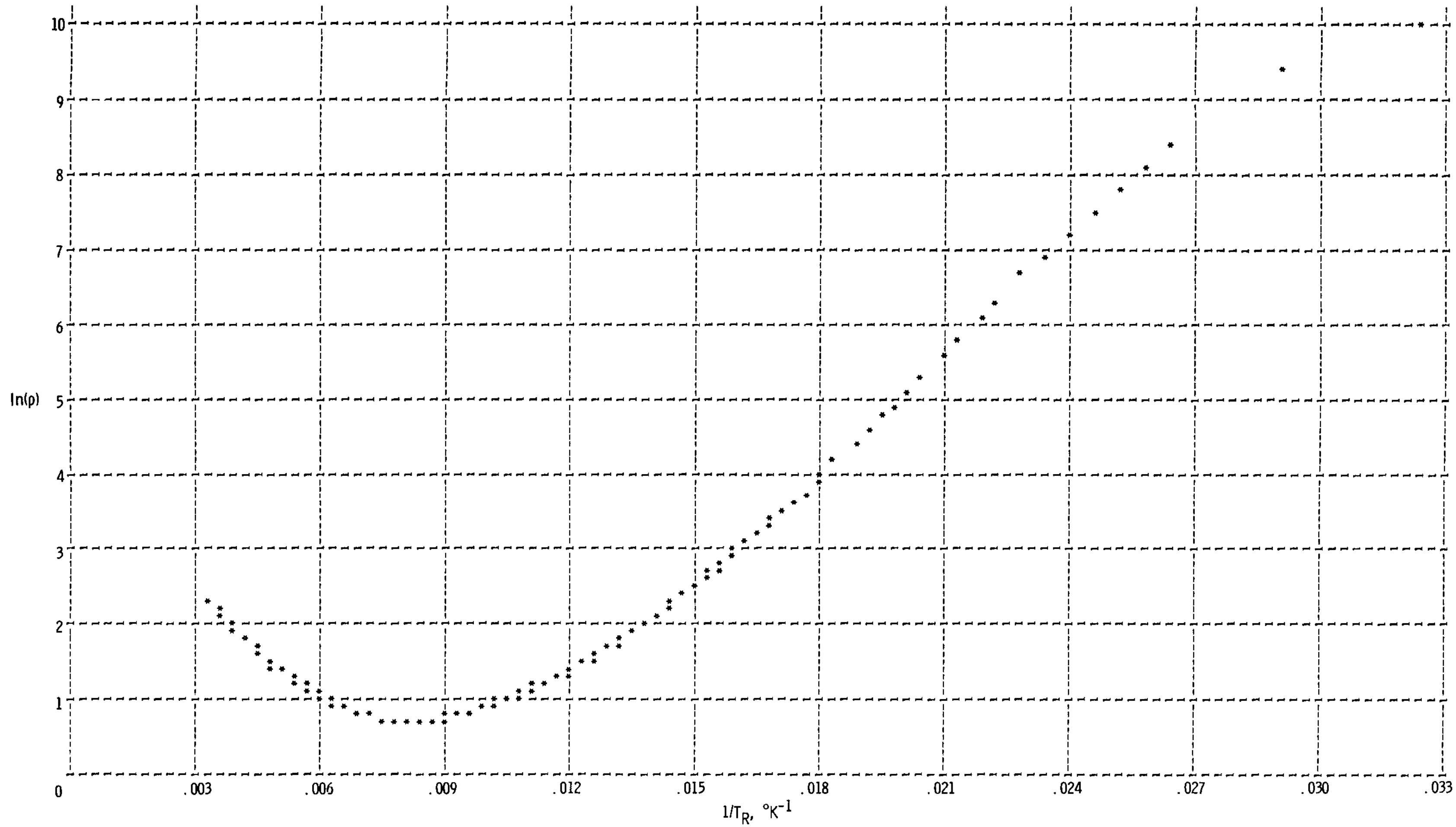
very near, but not shorted to, the metal disk, and discharging a condenser through the pressure-probe to metal-foil to sample to metal-electrode circuit, the metal foil is alloyed to the sample material. Several discharge pulses may be required and a reversal of the discharge pulse polarity may be necessary before a good ohmic contact is achieved. If the metal electrode is sharply pointed, which is desirable where small samples are involved, the electrode tip may also weld to the specimen. However, it can be removed easily without damaging the sample if care is exercised in breaking the weld. Caution is also advised in choosing the proper condenser and charging voltage values. Since the optimum of these values will vary, depending on the resistivity of the sample, it is advisable to practice on scrap pieces of material, using trial and error, until the best contact is perfected. A spark discharge that is too hot can thermally shock the sample to a degree that will cause it to fracture. However, this method proved to be simple compared with most alloying or plating techniques described in the literature. The method was used exclusively in welding aluminum foil to p-type silicon samples to obtain contacts that have remained ohmic from room temperature to the liquid-helium temperature region. Ohmic contacts are verified with an alternating-current curve tracer that visually displays both the forward and reverse I-V characteristics of the contact on an oscilloscope. This apparatus is also used to monitor the sample contacts at various temperatures.

RESULTS AND DISCUSSION

The raw data tapes that are punched out during each temperature run are corrected if necessary, and the required predata words are entered at the beginning of each tape. The resulting data tape is sent to the computing facility for processing, where the appropriate data reduction program is automatically selected by the computer and the data are processed by conventional methods. The computer-reduced data are presented in both tabulated columns and machine plots. The machine plots give a good qualitative presentation of the results; however, for a critical quantitative analysis, it is generally necessary to plot some of the tabulated results manually. Samples of the reduced data are presented in figure 7 and table III. The time saving realized by using computer processing alone is of the order of 3 to 4 weeks per sample.

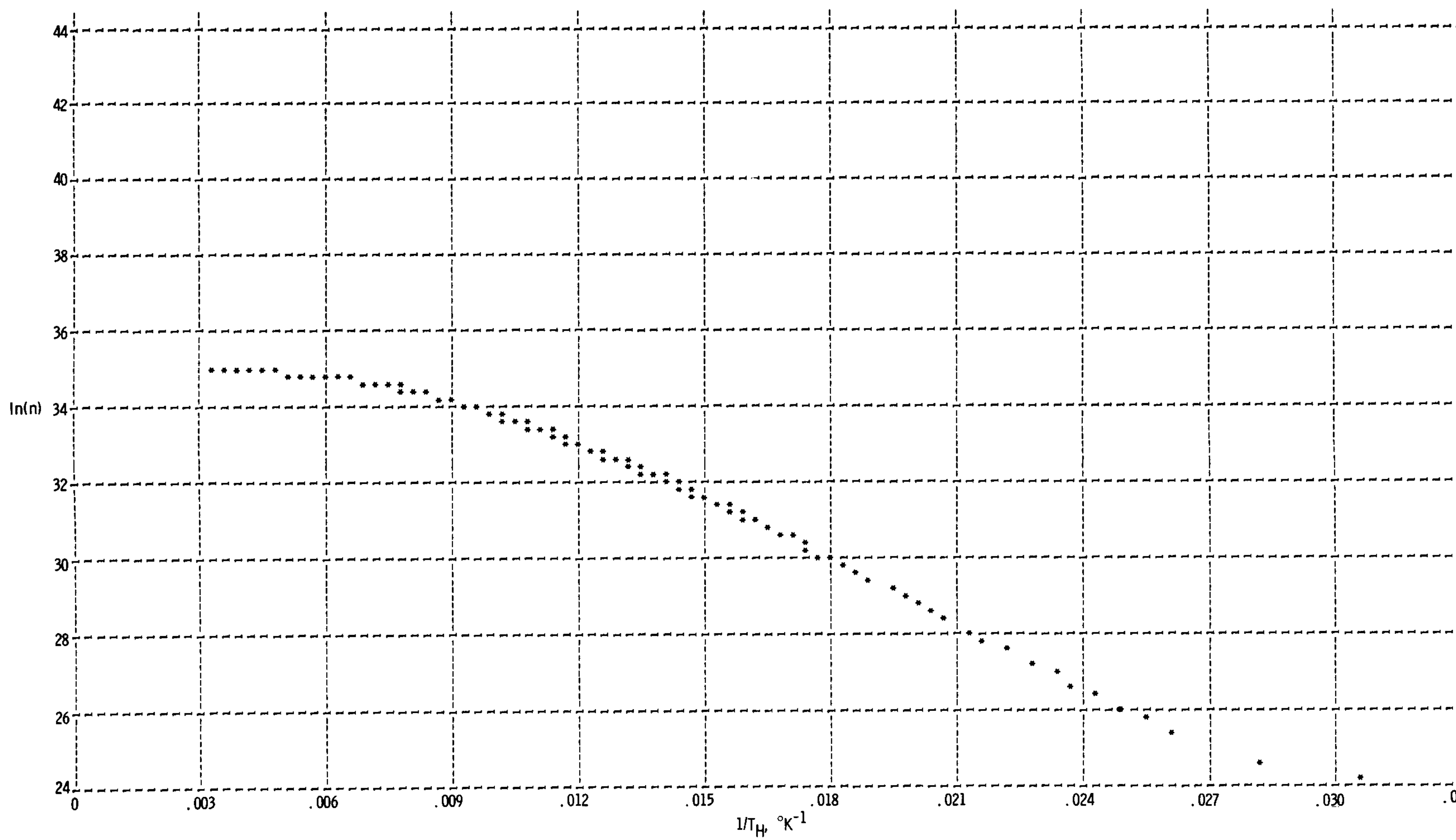
System Accuracy

The quoted accuracy of the digital voltmeter is 0.01 percent of the reading plus or minus one digit. The accuracy of the direct-current preamplifier is ±0.01 percent of



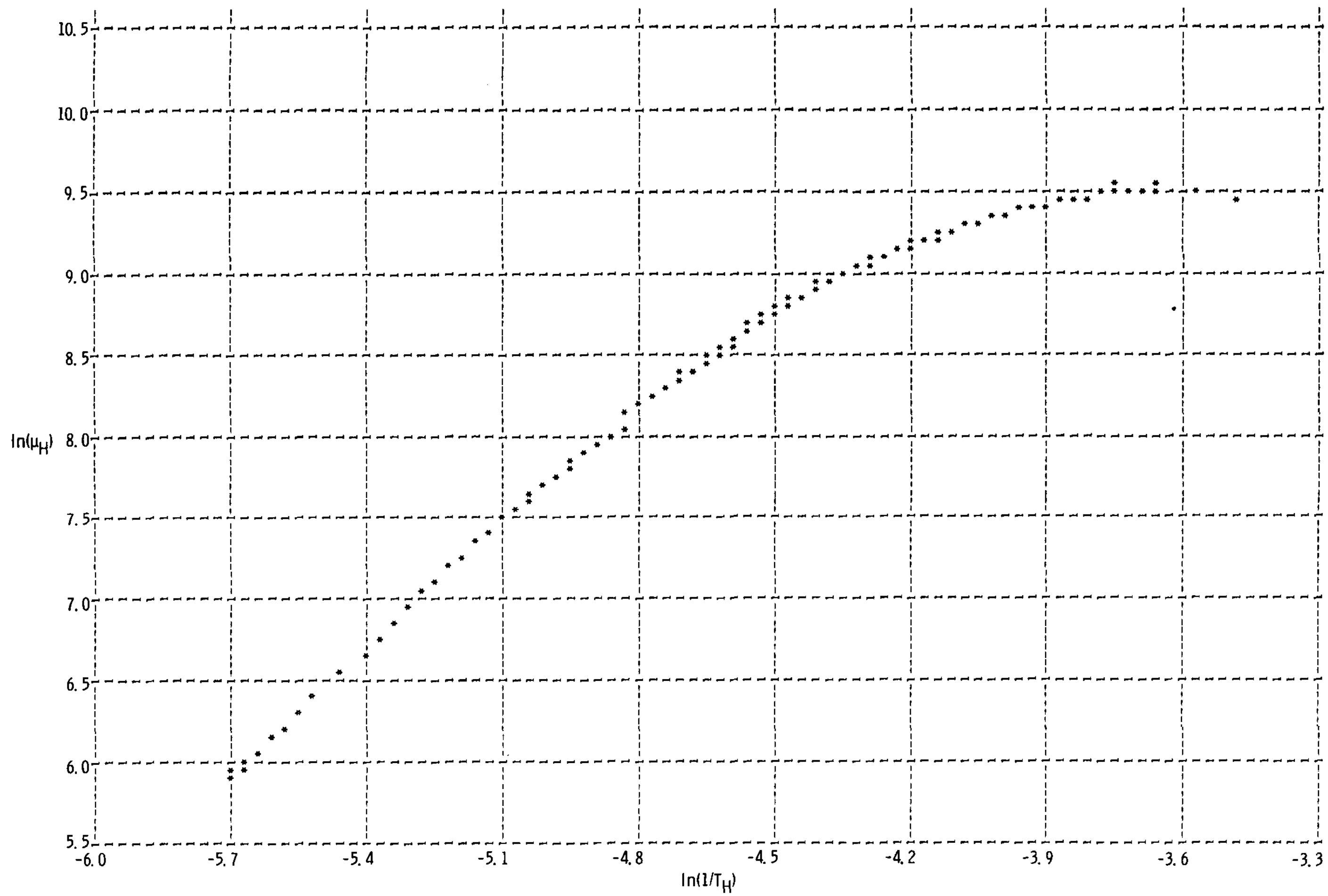
(a) $1/T_R$ against ln(ρ).

Figure 7. - Typical computer results.



(b) $1/T_H$ against ln(n).

Figure 7. - Continued.



(c) ln($1/T_H$) against ln(μ_H).

Figure 7. - Concluded.

TABLE III. - TYPICAL COMPUTER RESULTS

(a) Resistivity data

T_R	$1/T_R$	$T_R^{3/2}$	ρ	$\ln(\rho)$	σ
298.965	0.0033449	5169.29	10.1890	2.32131	0.98145E-01
298.965	0.0033449	5169.29	10.1890	2.32131	0.98145E-01
298.247	0.0033529	5150.68	10.1176	2.31427	0.98838E-01
295.778	0.0033809	5086.86	9.99066	2.30165	0.10009
293.645	0.0034055	5031.93	9.83995	2.28645	0.10163
291.470	0.0034309	4976.11	9.64561	2.26650	0.10367
287.666	0.0034763	4879.01	9.39178	2.23983	0.10648
284.640	0.0035132	4802.24	9.08190	2.20628	0.11011
272.829	0.0036653	4506.47	8.36835	2.12446	0.11950
267.121	0.0037436	4365.79	7.97589	2.07642	0.12538
255.252	0.0039177	4078.05	7.14739	1.96675	0.13991
248.853	0.0040184	3925.67	6.72322	1.90557	0.14874
233.210	0.0042880	3561.40	5.81939	1.76120	0.17184
225.380	0.0044369	3383.55	5.38730	1.68404	0.18562
217.871	0.0045899	3215.87	4.97256	1.60394	0.20110
209.850	0.0047653	3039.92	4.58823	1.52349	0.21795
202.947	0.0049274	2891.16	4.24748	1.44633	0.23543
195.967	0.0051029	2743.31	3.91465	1.36473	0.25545
189.321	0.0052820	2604.94	3.63730	1.29124	0.27493
183.894	0.0054379	2493.74	3.41542	1.22830	0.29279
178.745	0.0055946	2389.73	3.21731	1.16854	0.31082
173.874	0.0057513	2292.72	3.04543	1.11364	0.32836
169.095	0.0059138	2198.86	2.88844	1.06072	0.34621
164.114	0.0060933	2102.41	2.72996	1.00429	0.36631
160.045	0.0062483	2024.71	2.61901	0.96280	0.38182
156.039	0.0064087	1949.17	2.51203	0.92109	0.39808
152.610	0.0065526	1885.28	2.42367	0.88528	0.41260
148.998	0.0067115	1818.74	2.34958	0.85424	0.42561
145.635	0.0068665	1757.52	2.27318	0.82118	0.43991
142.643	0.0070105	1703.63	2.22676	0.80055	0.44908
139.843	0.0071509	1653.72	2.18210	0.78029	0.45828
137.027	0.0072978	1604.02	2.13853	0.76012	0.46761
133.633	0.0074832	1544.80	2.10289	0.74331	0.47554
130.462	0.0076650	1490.14	2.07121	0.72813	0.48281
127.284	0.0078564	1436.02	2.05141	0.71853	0.48747
124.154	0.0080545	1383.38	2.03953	0.71272	0.49031
121.079	0.0082590	1332.31	2.03953	0.71272	0.49031
118.046	0.0084713	1282.55	2.05141	0.71853	0.48747
115.249	0.0086768	1237.25	2.07517	0.73004	0.48189
112.643	0.0088776	1195.51	2.10289	0.74331	0.47554
110.105	0.0090823	1155.34	2.14249	0.76197	0.46675
107.829	0.0092739	1119.70	2.19002	0.78391	0.45662
105.731	0.0094580	1087.19	2.24546	0.80891	0.44534
103.810	0.0096330	1057.69	2.30090	0.83330	0.43461
102.944	0.0097140	1044.49	2.32862	0.84528	0.42944
101.498	0.0098524	1022.56	2.38407	0.86881	0.41945
100.120	0.0099881	1001.79	2.43951	0.89180	0.40992
98.9267	0.0101085	983.944	2.49495	0.91427	0.40081
97.8807	0.0102165	968.380	2.54644	0.93470	0.39271
96.9015	0.0103197	953.885	2.60188	0.95623	0.38434
96.0677	0.0104093	941.599	2.64544	0.97284	0.37801
95.2800	0.0104954	930.042	2.69693	0.99211	0.37079
94.6360	0.0105668	920.629	2.73653	1.00669	0.36543
94.1818	0.0106178	914.009	2.76821	1.01820	0.36124
93.8473	0.0106556	909.143	2.79197	1.02675	0.35817
93.4905	0.0106963	903.965	2.81969	1.03663	0.35465
93.1778	0.0107322	899.433	2.83950	1.04363	0.35218
92.9766	0.0107554	896.522	2.85929	1.05058	0.34974
92.3375	0.0108298	887.294	2.90682	1.06706	0.34402
91.7680	0.0108970	879.098	2.95038	1.08193	0.33894
91.3542	0.0109464	873.158	2.98998	1.09527	0.33445
91.0090	0.0109879	868.214	3.02167	1.10581	0.33094
90.6913	0.0110264	863.671	3.04939	1.11494	0.32793
30.8686	0.0323953	171.505	21345.5	9.96860	0.46848E-04
34.3662	0.0290983	201.464	11909.2	9.38507	0.83968E-04
37.8096	0.0264483	232.490	4588.88	8.43139	0.21792E-03
38.9099	0.0257004	242.711	3211.29	8.07443	0.31140E-03
39.7936	0.0251296	251.027	2390.88	7.77942	0.41826E-03
40.6871	0.0245778	259.529	1852.72	7.52441	0.53975E-03
41.6603	0.0240036	268.896	1351.33	7.20884	0.74001E-03
42.5935	0.0234777	277.981	1034.09	6.94128	0.96703E-03

TABLE III. - Continued. TYPICAL COMPUTER RESULTS

(a) Concluded. Resistivity data

T_R	$1/T_R$	$T_R^{3/2}$	ρ	$\ln(\rho)$	σ
43.6025	0.0229344	287.917	775.033	6.65291	0.12903E-02
44.7725	0.0223351	299.583	564.967	6.33677	0.17700E-02
45.8540	0.0218083	310.503	426.877	6.05650	0.23426E-02
46.9169	0.0213143	321.361	328.780	5.79539	0.30415E-02
47.8988	0.0208774	331.502	258.488	5.55485	0.38687E-02
48.8455	0.0204727	341.379	206.718	5.33135	0.48375E-02
49.7386	0.0201051	350.784	168.298	5.12574	0.59418E-02
50.5599	0.0197785	359.509	140.650	4.94628	0.71098E-02
51.4131	0.0194503	368.648	117.619	4.76745	0.85020E-02
52.3368	0.0191070	378.626	96.8719	4.57339	0.10323E-01
53.2890	0.0187656	389.006	79.9931	4.38194	0.12501E-01
54.2293	0.0184402	399.348	67.0349	4.20521	0.14918E-01
55.1008	0.0181486	409.013	56.3984	4.03244	0.17731E-01
55.9814	0.0178631	418.857	48.5991	3.88360	0.20577E-01
56.8146	0.0176011	428.242	42.2194	3.74288	0.23686E-01
57.6761	0.0173382	438.020	36.9163	3.60865	0.27088E-01
58.4544	0.0171073	446.916	32.8133	3.49083	0.30475E-01
59.2437	0.0168794	455.998	29.1786	3.37344	0.34272E-01
60.0245	0.0166599	465.042	26.2690	3.26839	0.38068E-01
60.8337	0.0164383	474.478	23.6865	3.16490	0.42218E-01
61.5642	0.0162432	483.050	21.6229	3.07375	0.46247E-01
62.3227	0.0160455	492.005	19.7925	2.98530	0.50524E-01
63.0392	0.0158632	500.513	18.4201	2.91344	0.54288E-01
63.7341	0.0156902	508.813	16.9320	2.82921	0.59060E-01
64.5583	0.0154899	518.715	15.4417	2.73707	0.64760E-01
65.2744	0.0153199	527.368	14.2733	2.65839	0.70061E-01
65.9832	0.0151554	535.982	13.2365	2.58298	0.75549E-01
66.7046	0.0149915	544.796	12.2926	2.50899	0.81350E-01
67.4191	0.0148326	553.573	11.4394	2.43706	0.87417E-01
68.0954	0.0146853	561.923	10.7212	2.37223	0.93273E-01
68.7662	0.0145420	570.246	10.0605	2.30861	0.99399E-01
69.4340	0.0144022	578.573	9.48331	2.24953	0.10545
70.1120	0.0142629	587.068	8.93268	2.18972	0.11195
70.8657	0.0141112	596.559	8.39866	2.12807	0.11907
71.5197	0.0139822	604.837	7.95883	2.07428	0.12565
72.1688	0.0138564	613.090	7.57891	2.02537	0.13195
72.8142	0.0137336	621.332	7.22500	1.97755	0.13841
73.3932	0.0136252	628.759	6.92692	1.93542	0.14436
73.7689	0.0135558	633.592	6.74529	1.90884	0.14825
74.0805	0.0134988	637.611	6.60625	1.88802	0.15137
74.3441	0.0134510	641.017	6.48645	1.86972	0.15417
74.6085	0.0134033	644.439	6.37107	1.85177	0.15696
74.9479	0.0133426	648.843	6.23262	1.82980	0.16045
75.3181	0.0132770	653.655	6.08997	1.80664	0.16420
75.7802	0.0131961	659.680	5.91585	1.77763	0.16904
76.3144	0.0131037	666.668	5.74023	1.74750	0.17421
77.3498	0.0129283	680.282	5.40256	1.68687	0.18510
77.4105	0.0129181	681.083	5.36832	1.68051	0.18628
78.4388	0.0127488	694.699	5.06623	1.62260	0.19739
79.6974	0.0125475	711.486	4.75156	1.55847	0.21046
80.1009	0.0124843	716.896	4.64965	1.53679	0.21507
80.7104	0.0123900	725.094	4.52682	1.51002	0.22091
81.3865	0.0122870	734.225	4.37071	1.47493	0.22880
82.7832	0.0120797	753.205	4.09807	1.41051	0.24402
84.2186	0.0118739	772.880	3.84958	1.34796	0.25977
85.4539	0.0117022	789.947	3.67232	1.30082	0.27231
86.4690	0.0115648	804.064	3.52878	1.26095	0.28338
87.6276	0.0114119	820.279	3.38830	1.22033	0.29513
88.5809	0.0112891	833.700	3.27894	1.18752	0.30498
89.5717	0.0111642	847.728	3.17380	1.15493	0.31508
90.4461	0.0110563	860.171	3.08867	1.12774	0.32376
91.1774	0.0109676	870.624	3.02271	1.10615	0.33083
91.9003	0.0108813	880.999	2.96044	1.08534	0.33779
92.5702	0.0108026	890.649	2.90327	1.06584	0.34444
93.2359	0.0107255	900.274	2.85223	1.04810	0.35060
93.8710	0.0106529	909.489	2.80425	1.03114	0.35660
94.5277	0.0105789	919.049	2.76103	1.01560	0.36218
95.2253	0.0105014	929.241	2.71544	0.99895	0.36826
95.8459	0.0104334	938.340	2.67563	0.98418	0.37374

TABLE III. - Continued. TYPICAL COMPUTER RESULTS

(b) Hall data

T_H	$1/T_H$	$\ln(1/T_H)$	$T_H^{3/2}$	R_H	$\ln(R_H)$	n	ln(n)	μ_H	$\ln(\mu_H)$
297.742	0.0033586	-5.69623	5137.59	3720.76	8.22168	0.16776E 16	35.0561	368.699	5.90998
298.743	0.0033474	-5.69958	5163.52	3721.55	8.22190	0.16772E 16	35.0559	366.047	5.90276
297.326	0.0033633	-5.69483	5126.84	3720.39	8.22158	0.16777E 16	35.0562	369.444	5.91200
295.208	0.0033874	-5.68768	5072.15	3728.44	8.22374	0.16741E 16	35.0541	374.704	5.92614
294.896	0.0033910	-5.68662	5064.10	3737.94	8.22629	0.16699E 16	35.0515	376.494	5.93090
290.338	0.0034443	-5.67105	4947.16	3750.69	8.22969	0.16642E 16	35.0481	391.917	5.97105
287.339	0.0034802	-5.66066	4870.71	3767.62	8.23420	0.16567E 16	35.0436	402.594	5.99793
282.263	0.0035428	-5.64284	4742.20	3790.58	8.24028	0.16467E 16	35.0375	424.085	6.04993
272.877	0.0036647	-5.60902	4507.66	3843.79	8.25421	0.16239E 16	35.0236	459.166	6.12941
268.004	0.0037313	-5.59100	4387.46	3877.99	8.26307	0.16095E 16	35.0147	482.541	6.17907
254.918	0.0039228	-5.54094	4070.07	3959.19	8.28380	0.15765E 16	34.9940	555.654	6.32015
247.930	0.0040334	-5.51314	3903.84	4006.05	8.29556	0.15581E 16	34.9822	600.619	6.39796
232.695	0.0042974	-5.44975	3549.71	4106.77	8.32039	0.15199E 16	34.9574	709.139	6.56405
224.689	0.0044506	-5.41472	3368.01	4160.25	8.33333	0.15003E 16	34.9445	777.742	6.65640
217.267	0.0046026	-5.38113	3202.51	4211.43	8.34556	0.14821E 16	34.9322	851.889	6.74746
209.265	0.0047786	-5.34360	3027.23	4268.50	8.35902	0.14623E 16	34.9188	936.203	6.84183
202.333	0.0049423	-5.30992	2878.06	4324.03	8.37194	0.14435E 16	34.9059	1025.08	6.93253
195.276	0.0051210	-5.27441	2728.81	4381.23	8.38508	0.14247E 16	34.8927	1127.49	7.02775
188.943	0.0052926	-5.24145	2597.15	4444.90	8.39951	0.14043E 16	34.8783	1227.24	7.11252
183.294	0.0054557	-5.21109	2481.55	4503.00	8.41250	0.13861E 16	34.8653	1327.40	7.19098
178.181	0.0056123	-5.18280	2378.45	4562.08	8.42553	0.13682E 16	34.8523	1426.79	7.26319
173.328	0.0057694	-5.15519	2281.94	4631.80	8.44070	0.13476E 16	34.8371	1529.90	7.33296
168.689	0.0059281	-5.12806	2190.94	4703.05	8.45597	0.13272E 16	34.8218	1635.55	7.39973
163.581	0.0061132	-5.09731	2092.18	4799.39	8.47624	0.13005E 16	34.8016	1767.45	7.47730
159.537	0.0062681	-5.07228	2015.09	4883.98	8.49372	0.12780E 16	34.7841	1874.51	7.53611
155.617	0.0064260	-5.04740	1941.27	4983.36	8.51386	0.12525E 16	34.7639	1992.41	7.59710
152.232	0.0065689	-5.02541	1878.28	5089.58	8.53495	0.12264E 16	34.7428	2106.69	7.65287
148.445	0.0067365	-5.00021	1808.62	5212.86	8.55888	0.11974E 16	34.7189	2230.57	7.71001
145.321	0.0068813	-4.97894	1751.82	5335.90	8.58221	0.11698E 16	34.6956	2352.38	7.76318
142.364	0.0070243	-4.95838	1698.63	5469.36	8.60692	0.11412E 16	34.6709	2461.12	7.80837
139.540	0.0071664	-4.93835	1648.34	5614.76	8.63315	0.11117E 16	34.6446	2578.65	7.85502
136.579	0.0073218	-4.91690	1596.15	5782.75	8.66263	0.10794E 16	34.6152	2710.04	7.90472
133.268	0.0075037	-4.89236	1538.47	6011.75	8.70147	0.10383E 16	34.5763	2863.78	7.95990
130.080	0.0076876	-4.86815	1483.59	6260.79	8.74206	0.99697E 15	34.5357	3026.25	8.01508
126.928	0.0078785	-4.84362	1430.00	6558.80	8.78856	0.95167E 15	34.4892	3199.33	8.07070
123.828	0.0080757	-4.81889	1377.94	6906.75	8.84025	0.90373E 15	34.4375	3386.45	8.12754
120.719	0.0082837	-4.79347	1326.37	7300.52	8.89570	0.85498E 15	34.3821	3577.04	8.18229
117.699	0.0084963	-4.76813	1276.90	7751.38	8.95563	0.80525E 15	34.3222	3773.15	8.23567
114.960	0.0086986	-4.74459	1232.60	8249.34	9.01789	0.75664E 15	34.2599	3969.39	8.28637
112.373	0.0088989	-4.72183	1191.23	8793.05	9.08172	0.70986E 15	34.1961	4173.07	8.33641
109.856	0.0091028	-4.69917	1151.43	9387.64	9.14715	0.66490E 15	34.1307	4371.06	8.38276
107.570	0.0092963	-4.67814	1115.67	10013.8	9.21171	0.62332E 15	34.0661	4558.21	8.42469
105.544	0.0094748	-4.65912	1084.30	10666.9	9.27490	0.58516E 15	34.0029	4739.01	8.46358
103.616	0.0096510	-4.64070	1054.73	11334.3	9.33559	0.55070E 15	33.9422	4912.79	8.49960
102.758	0.0097316	-4.63237	1041.65	11671.5	9.36490	0.53479E 15	33.9129	4996.82	8.51656
101.332	0.0098686	-4.61840	1020.04	12285.5	9.41617	0.50806E 15	33.8616	5138.72	8.54456
99.9426	0.0100057	-4.60460	999.140	12916.2	9.46624	0.48325E 15	33.8116	5276.81	8.57108
98.7724	0.0101243	-4.59282	981.642	13501.3	9.51054	0.46231E 15	33.7673	5395.03	8.59323
97.7843	0.0102266	-4.58276	966.949	14066.3	9.55154	0.44374E 15	33.7263	5512.09	8.61470
96.8098	0.0103295	-4.57275	952.531	14620.4	9.59018	0.42692E 15	33.6876	5608.85	8.63210
95.9894	0.0104178	-4.56424	940.449	15131.7	9.62455	0.41250E 15	33.6533	5696.98	8.64769
95.2135	0.0105027	-4.55612	929.069	15639.2	9.65754	0.39911E 15	33.6203	5758.47	8.65843
94.5961	0.0105713	-4.54962	920.046	16061.5	9.68418	0.38862E 15	33.5936	5849.98	8.67419
94.1534	0.0106210	-4.54493	913.596	16382.5	9.70397	0.38100E 15	33.5738	5911.07	8.68458
93.8087	0.0106600	-4.54126	908.583	16644.1	9.71981	0.37502E 15	33.5580	5955.00	8.69199
93.4516	0.0107007	-4.53744	903.400	16902.0	9.73519	0.36929E 15	33.5426	5983.73	8.69680
93.1778	0.0107322	-4.53451	899.433	17129.5	9.74856	0.36439E 15	33.5292	6032.59	8.70493
92.9526	0.0107582	-4.53209	896.175	17330.9	9.76025	0.36015E 15	33.5176	6055.77	8.70877
92.3375	0.0108298	-4.52545	887.294	17827.7	9.78851	0.35012E 15	33.4893	6133.08	8.72145
91.7492	0.0108993	-4.51906	878.827	18293.2	9.81428	0.34121E 15	33.4635	6196.48	8.73174
91.3395	0.0109482	-4.51458	872.947	18667.7	9.83455	0.33436E 15	33.4432	6237.73	8.73837
90.9667	0.0109930	-4.51049	867.608	19003.1	9.85236	0.32846E 15	33.4254	6281.27	8.74533
90.6790	0.0110279	-4.50733	863.495	19287.2	9.86720	0.32362E 15	33.4106	6320.86	8.75161
32.7724	0.0305135	-3.48959	187.612	0.20367E 09	19.1320	0.30647E 11	24.1458	12564.7	9.43865
35.4070	0.0282430	-3.56691	210.685	0.13065E 09	18.6881	0.47774E 11	24.5897	13474.1	9.50853
38.3126	0.0261011	-3.64578	237.144	0.53968E 08	17.8039	0.11566E 12	25.4739	13631.1	9.52011
39.3781	0.0253948	-3.67321	247.105	0.38299E 08	17.4609	0.16298E 12	25.8169	13793.4	9.53194
40.1818	0.0248869	-3.69341	254.708	0.29280E 08	17.1924	0.21318E 12	26.0854	13573.5	9.51588
40.9975	0.0243917	-3.71351	262.504	0.22721E 08	16.9388	0.27472E 12	26.3390	13422.0	9.50465
42.0121	0.0238027	-3.73796	272.309	0.16928E 08	16.6445	0.36874E 12	26.6333	13742.7	9.52826
42.8705	0.0233260	-3.75818	280.697	0.12908E 08	16.3734	0.48355E 12	26.9044	13404.8	9.50337
43.8746	0.0227922	-3.78134	290.616	0.96786E 07	16.0854	0.64491E 12	27.1924	13328.0	9.49762
44.9059	0.0222688	-3.80457	300.922	0.70291E 07	15.7656	0.88799E 12	27.5122	12828.4	9.45941

TABLE III. - Concluded. TYPICAL COMPUTER RESULTS

(b) Concluded. Hall data

T_H	$1/T_H$	$\ln(1/T_H)$	$T_H^{3/2}$	R_H	$\ln(R_H)$	n	ln(n)	μ_H	$\ln(\mu_H)$
46.0724	0.0217050	-3.83021	312.724	0.52719E 07	15.4779	0.11840E 13	27.7999	12961.8	9.46976
47.0886	0.0212365	-3.85203	323.128	0.39864E 07	15.1984	0.15658E 13	28.0794	12595.8	9.44112
48.0891	0.0207947	-3.87305	333.480	0.30804E 07	14.9406	0.20263E 13	28.3372	12416.8	9.42681
49.0125	0.0204030	-3.89207	343.131	0.24543E 07	14.7134	0.25432E 13	28.5644	12300.3	9.41738
49.8830	0.0200469	-3.90968	352.313	0.20144E 07	14.5158	0.30986E 13	28.7620	12325.4	9.41942
50.7234	0.0197148	-3.92639	361.253	0.16542E 07	14.3189	0.37732E 13	28.9590	12142.2	9.40445
51.5546	0.0193969	-3.94264	370.170	0.13694E 07	14.1299	0.45582E 13	29.1479	11965.7	9.38980
52.4963	0.0190490	-3.96074	380.358	0.11167E 07	13.9259	0.55895E 13	29.3519	11874.2	9.38212
53.4266	0.0187172	-3.97831	390.514	0.91151E 06	13.7229	0.68478E 13	29.5549	11671.6	9.36491
54.3850	0.0183874	-3.99609	401.069	0.75163E 06	13.5300	0.83044E 13	29.7478	11539.6	9.35354
55.2358	0.0181042	-4.01161	410.517	0.62839E 06	13.3509	0.99330E 13	29.9269	11383.3	9.33990
56.1337	0.0178146	-4.02774	420.567	0.53602E 06	13.1919	0.11645E 14	30.0859	11300.6	9.33261
56.9836	0.0175489	-4.04276	430.155	0.45852E 06	13.0358	0.13613E 14	30.2420	11134.9	9.31784
57.8063	0.0172992	-4.05710	439.504	0.39683E 06	12.8913	0.15729E 14	30.3865	10953.1	9.30138
58.6017	0.0170644	-4.07076	448.606	0.34885E 06	12.7624	0.17893E 14	30.5154	10855.7	9.29244
59.3708	0.0168433	-4.08380	457.466	0.30826E 06	12.6387	0.20248E 14	30.6391	10738.9	9.28162
60.1328	0.0166299	-4.09656	466.302	0.27352E 06	12.5191	0.22820E 14	30.7587	10551.1	9.26399
60.9407	0.0164094	-4.10990	475.731	0.24472E 06	12.4079	0.25506E 14	30.8699	10465.1	9.25581
61.6883	0.0162105	-4.12209	484.512	0.22104E 06	12.3061	0.28238E 14	30.9717	10366.2	9.24631
62.4283	0.0160184	-4.13402	493.256	0.19990E 06	12.2056	0.31225E 14	31.0722	10204.1	9.23054
63.1094	0.0158455	-4.14487	501.350	0.18391E 06	12.1222	0.33940E 14	31.1556	10066.1	9.21693
63.8546	0.0156606	-4.15661	510.257	0.16736E 06	12.0279	0.37296E 14	31.2499	10013.1	9.21165
64.6783	0.0154611	-4.16943	520.161	0.15101E 06	11.9251	0.41335E 14	31.3527	9904.72	9.20077
65.3927	0.0152922	-4.18041	528.803	0.13838E 06	11.8377	0.45108E 14	31.4401	9813.75	9.19154
66.1019	0.0151281	-4.19120	537.429	0.12706E 06	11.7524	0.49124E 14	31.5254	9713.48	9.18127
66.8043	0.0149691	-4.20177	546.017	0.11652E 06	11.6658	0.53569E 14	31.6120	9571.36	9.16653
67.5354	0.0148070	-4.21265	555.005	0.10748E 06	11.5850	0.58076E 14	31.6928	9497.87	9.15882
68.2109	0.0146604	-4.22260	563.353	99520.1	11.5081	0.62719E 14	31.7697	9382.07	9.14656
68.8966	0.0145145	-4.23261	571.870	93063.5	11.4410	0.67070E 14	31.8368	9355.26	9.14369
69.5477	0.0143786	-4.24201	579.995	86701.8	11.3702	0.71992E 14	31.9076	9232.49	9.13048
70.2252	0.0142399	-4.25171	588.490	80859.7	11.3005	0.77193E 14	31.9773	9134.15	9.11978
70.9460	0.0140952	-4.26192	597.575	74939.2	11.2244	0.83292E 14	32.0534	8980.57	9.10282
71.6304	0.0139605	-4.27152	606.242	70097.6	11.1576	0.89045E 14	32.1202	8879.82	9.09154
72.2635	0.0138382	-4.28032	614.298	66408.1	11.1036	0.93992E 14	32.1742	8822.67	9.08508
72.9244	0.0137128	-4.28942	622.743	62577.3	11.0442	0.99746E 14	32.2336	8729.76	9.07449
73.4719	0.0136106	-4.29690	629.770	59479.8	10.9934	0.10494E 15	32.2844	8634.17	9.06348
73.8159	0.0135472	-4.30157	634.198	57738.1	10.9637	0.10811E 15	32.3141	8586.48	9.05794
74.1266	0.0134904	-4.30577	638.206	56235.5	10.9373	0.11099E 15	32.3405	8539.53	9.05246
74.4215	0.0134370	-4.30974	642.018	55158.9	10.9180	0.11316E 15	32.3598	8548.22	9.05348
74.6704	0.0133922	-4.31308	645.242	53872.1	10.8944	0.11586E 15	32.3834	8489.38	9.04657
75.0099	0.0133316	-4.31762	649.648	52320.7	10.8651	0.11930E 15	32.4127	8426.95	9.03919
75.3795	0.0132662	-4.32254	654.456	50831.3	10.8363	0.12279E 15	32.4415	8378.58	9.03343
75.8714	0.0131802	-4.32904	660.872	48928.5	10.7981	0.12757E 15	32.4797	8312.90	9.02556
76.3616	0.0130956	-4.33548	667.287	47137.9	10.7608	0.13242E 15	32.5170	8233.92	9.01602
77.3981	0.0129202	-4.34896	680.920	43666.9	10.6843	0.14294E 15	32.5935	8123.63	9.00253
77.4726	0.0129078	-4.34992	681.903	43214.6	10.6739	0.14444E 15	32.6039	8077.40	8.99683
78.5747	0.0127267	-4.36405	696.505	39813.2	10.5920	0.15678E 15	32.6858	7911.60	8.97609
79.7740	0.0125354	-4.37920	712.512	36746.5	10.5118	0.16986E 15	32.7660	7765.20	8.95741
80.1898	0.0124704	-4.38440	718.090	35659.1	10.4818	0.17504E 15	32.7960	7698.87	8.94883
80.8109	0.0123746	-4.39211	726.449	34350.8	10.4444	0.18171E 15	32.8334	7627.39	8.93950
81.5228	0.0122665	-4.40088	736.069	32744.0	10.3965	0.19062E 15	32.8813	7537.55	8.92765
82.9565	0.0120545	-4.41832	755.571	29814.8	10.3028	0.20935E 15	32.9750	7328.99	8.89959
84.4353	0.0118434	-4.43599	775.865	27177.0	10.2101	0.22967E 15	33.0677	7117.23	8.87027
85.5711	0.0116862	-4.44935	791.572	25448.7	10.1444	0.24527E 15	33.1334	6961.27	8.84812
86.6248	0.0115440	-4.46159	806.238	24014.9	10.0864	0.25991E 15	33.1914	6842.06	8.83084
87.7695	0.0113935	-4.47471	822.271	22619.2	10.0266	0.27595E 15	33.2512	6707.90	8.81104
88.7187	0.0112716	-4.48547	835.647	21508.2	9.97619	0.29021E 15	33.3016	6588.89	8.79314
89.7413	0.0111431	-4.49693	850.136	20380.9	9.92235	0.30626E 15	33.3554	6455.18	8.77264
90.5566	0.0110428	-4.50597	861.748	19529.8	9.87970	0.31960E 15	33.3981	6359.49	8.75770
91.3011	0.0109528	-4.51416	872.397	18857.3	9.84466	0.33100E 15	33.4331	6286.16	8.74611
92.0144	0.0108679	-4.52194	882.640	18253.4	9.81211	0.34195E 15	33.4657	6195.06	8.73151
92.6893	0.0107887	-4.52925	892.369	17648.7	9.77842	0.35367E 15	33.4994	6106.02	8.71703
93.3456	0.0107129	-4.53631	901.864	17150.8	9.74980	0.36394E 15	33.5280	6042.81	8.70662
94.0001	0.0106383	-4.54330	911.365	16601.7	9.71726	0.37597E 15	33.5605	5951.96	8.69148
94.6276	0.0105677	-4.54995	920.507	16211.2	9.69346	0.38503E 15	33.5843	5919.91	8.68608
95.2994	0.0104932	-4.55702	930.327	15735.8	9.66370	0.39666E 15	33.6141	5836.31	8.67185
95.9351	0.0104237	-4.56367	939.651	15296.2	9.63536	0.40806E 15	33.6424	5742.94	8.65573

the gain setting. The digital voltmeter-preamplifier combination has been frequently calibrated against a type K-3 potentiometer and has always been within the quoted accuracy. The overall accuracy of the entire system is estimated to be ±0.1 percent or better.

Accuracy of Hall Effect and Resistivity Data

The absolute values of the Hall effect and resistivity data are estimated to be accurate to ±1 percent for both n-type and p-type silicon single crystals that have been measured by the system. The largest source of error for these measurements is introduced in the calculations in the sample dimension and magnetic field terms. Since the samples are usually cut by air abrasive techniques, it is not uncommon to see 1-percent differences in the width of the samples between the front and back surfaces.

Gaussmeter Calibration

The gaussmeter probe was calibrated initially against a rotating coil gaussmeter that had an accuracy of ±0.1 percent or ±2 gauss (0.0002 T). The Hall-type probe was later calibrated against a 9.78-kilogauss (0.978 T) standard magnet that was accurate to ±0.5 percent. Agreement between the two sources of calibration was 0.33 percent, which falls well within the 0.5 percent accuracy stated for the standard magnet. Since both the probe current and the Hall voltage of the gaussmeter probe are measured with the 0.01-percent digital voltmeter, the magnetic field measurements are estimated to be accurate to better than ±0.5 percent.

Thermocouple Calibration

Standard calibration tables were used as a basis for the temperature calculations associated with the two copper-constantan thermocouples mounted in the sample holder suspension system. To establish the calibration curve for temperatures lower than the melting point of ice, tables were obtained from a survey by Billing (ref. 3). For temperatures above the ice point, Leads and Northrup tables were used. After the two thermocouples were mounted in the sample suspension system, conventional fixed-point temperature calibrations were conducted at the boiling point of helium (4.2150° K), the boiling point of nitrogen (77.349° K), the melting point of ice (273.16° K), and the boiling point of water (373.16° K). The fixed-point calibrations were used to perform a parallel shift of the curve obtained with the referenced calibration tables, and a computer-controlled curve fit routine was then used to calculate the actual temperature. The maximum deviation measured between the two thermocouples during the fixed-point calibrations was 0.2°, which occurred only at the boiling point of water. There was full agreement between the thermocouples for the remaining three fixed-point calibrations. The maximum error due to the computer curve fitting for all temperatures calculated above 15° K is 0.5 percent or less. The maximum error between 4.2° and 15.0° K is 10 percent or less.

CONCLUDING REMARKS

A fully function-programmable, automated Hall effect and resistivity apparatus was constructed and put into operation for studying the electrical transport properties of semiconductors. System features include automatic scanning and measurement of up to 50 signal inputs, the capacity to program automatic switching of 10 operational functions normally performed manually for each input, and a computer-compatible recording output. The system has been used primarily for Hall effect and resistivity studies of cadmium sulfide crystals and films and for both n-type and p-type silicon crystals at temperatures between 4.2° and 300° K. The useful range of the system was extended to include some materials with resistivities up to 10^{10} ohm-centimeters. By following rather specialized techniques in sample preparation, sample mounting, and measurement procedures, an absolute accuracy of approximately ±1 percent was achieved for the Hall and resistivity results. An overall system-measuring accuracy of ±0.1 percent or better was calculated.

It is concluded that, with the careful design and application of the automated apparatus described, accurate measurements can be obtained. It is further concluded that a time saving of 3 to 4 man-weeks per sample can be realized in the automatic collection and computer reduction of data.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 26, 1967,
120-33-01-09-22.

APPENDIX - SYMBOLS

g	geometric correction factor determined by sample length to width ratio
l	sample resistivity probe spacing, cm
n	carrier concentration, cm^{-3}
R_H	Hall coefficient, cm^3/C
R_s	standard resistor used for sample current determinations, ohm
T_H	temperature associated with Hall measurements, ^oK
T_R	temperature associated with resistivity measurements, ^oK
t	sample thickness, cm
V_{H+}	magnetic field strength, normal polarity, V
V_{H-}	magnetic field strength, reverse polarity, V
V_{H^+,I^+}	Hall voltage, magnetic field normal, sample current positive, V
V_{H^+,I^-}	Hall voltage, magnetic field normal, sample current negative, V
V_{H^-,I^+}	Hall voltage, magnetic field reversed, sample current positive, V
V_{H^-,I^-}	Hall voltage, magnetic field reversed, sample current negative, V
$V_{I,H}$	Gaussmeter probe current, V
$V_{I^+,H}$	sample current for Hall measurements, positive polarity, V
$V_{I^-,H}$	sample current for Hall measurements, negative polarity, V
$V_{I^+,R}$	sample current for resistivity measurements, positive polarity, V
$V_{I^-,R}$	sample current for resistivity measurements, negative polarity, V
V_{R+}	resistivity voltage, positive sample current, V
V_{R-}	resistivity voltage, negative sample current, V
$V_{T,A1}$	thermocouple A, measurement 1, V
$V_{T,A2}$	thermocouple A, measurement 2, V
$V_{T,A3}$	thermocouple A, measurement 3, V
$V_{T,B1}$	thermocouple B, measurement 1, V
$V_{T,B2}$	thermocouple B, measurement 2, V
$V_{T,B3}$	thermocouple B, measurement 3, V
w	sample width, cm
μ_H	Hall mobility, $cm^2/(V)(sec)$
ρ	resistivity, ohm-cm
σ	conductivity, $(ohm\text{-}cm)^{-1}$

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