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Semiconductor Measurement Technology:

An Automated Photovoltaic System for the Measurement of Resistivity Variations in High-Resistivity Circular Silicon Slices

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This activity was supported by

The Department of Energy
Division of Electric Energy Systems
Washington, D.C. 20545

U.S. DEPARTMENT OF COMMERCE

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Issued November 1979

Library of Congress Catalog Card Number: 79-600178

National Bureau of Standards Special Publication 400-52
Nat. Bur. Stand. (U.S.), Spec. Publ. 400-52, 41 pages (Nov. 1979)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1979

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Stock No. 003-003-02138-5 Price $2

(Add 25 percent additional for other than U.S. mailing).

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979 O—311-065 (266)

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ABSTRACT

This report describes an automated photovoltaic system for nondestructive measurement of resistivity variations of high-resistivity circular silicon slices. The computer-based system for making the measurements is described, detailed construction diagrams are given to facilitate reproduction of the system, and a listing of the computer program for controlling the system is given. Comparisons between resistivity profiles determined using the automated photovoltaic system and the four-probe technique indicate that the photovoltaic system is adequate for production screening and incoming inspection of high-resistivity float-zoned silicon slices.

Key Words: Automation; bulk photovoltaic effect; computer control; homogeneity; measurement method; nondestructive testing; photoconductivity; power devices; resistivity variation.

1. INTRODUCTION

The overall objective of this task was to evaluate the feasibility of the photovoltaic method [1,2] as a rapid, nondestructive technique for characterizing the resistivity uniformity of high-resistivity, large-diameter silicon slices intended for fabrication of high-power devices. In the photovoltaic technique, a light spot is scanned along a slice diameter. The photovoltage and photoinduced change in specimen resistance are measured as a function of position along the slice diameter. From these two measurements, the variation in resistivity along the diameter can be computed.

Most of the results of this work have already been published [3-6]. A copy of reference [3] which contains a brief description of the theory of the bulk photovoltaic effect, a description of the measurement procedure and the apparatus employed, and a discussion of the results obtained for float-zoned (FZ) silicon is included as Appendix A to this report. Discussion of the characterization of the photovoltaic system, the illumination wavelength, surface finish, measurement time, theoretical analysis, experimental results, and extension to neutron transmutation doped (NTD) silicon is given elsewhere [6]. A more detailed description of the mathematical analysis has been prepared for separate publication [7].

This report provides the details necessary to replicate and use the measurement system. In the next section, the computer-based system for making the measurement is described, and detailed construction diagrams are given to facilitate reproduction of the system. Procedures for using the system are outlined in section 3. The complete listing of the computer program for controlling the system is given in Appendix B.

2. SYSTEM CONSTRUCTION

A picture and diagram of the completed photovoltaic system are shown in figure 1. A simplified block diagram can be found in Appendix A, figure 3.

In table 1 are listed the major components of the system which were commercially purchased. The multiprogrammer is an integral part of the computer/controller system.

A diagram of the electrical switching circuitry employed for the measurements is shown in figure 2. The digital input boards (Hewlett Packard Model 69431A) and relay boards (Hewlett Packard Model 69433A) are physically located within the multiprogrammer. The digital panel meter is used to measure the current in the specimen during the measurement of the photoinduced change in specimen resistance, ΔR, as well as to measure the current and voltages for the measurement of the van der Pauw average slice resistivity.

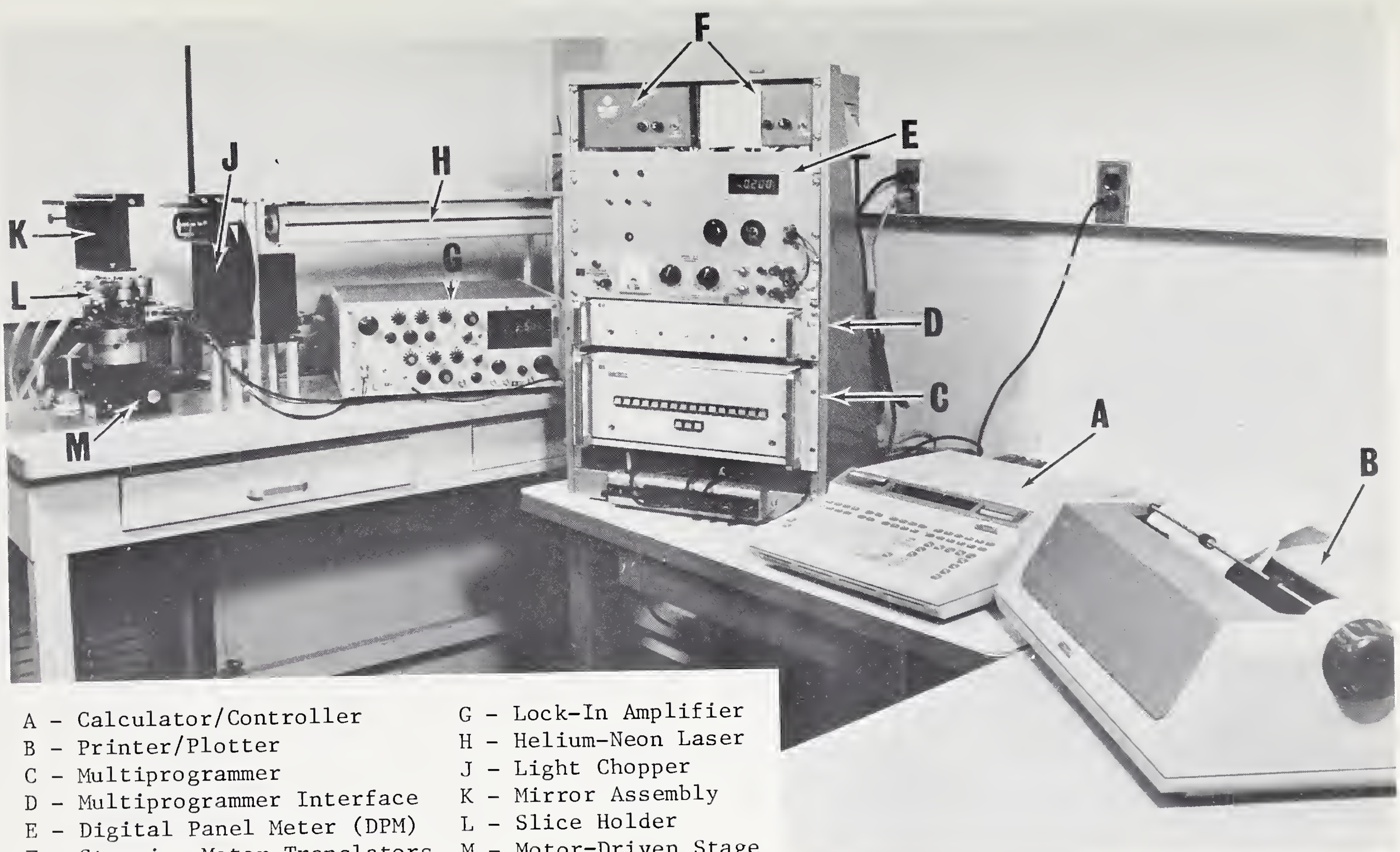
A diagram of the circuitry to control the stepping motor is shown in figure 3. Both the relay board and motor control card (Hewlett Packard Model 69335A) are physically located in the multiprogrammer.

The mechanical layout of the laser support (constructed at NBS), light chopper (commercial), x-y stage (commercial), and mirror assembly (constructed at NBS) is shown in figure 4. The support metal is 1/2-in. (12.7-mm) thick aluminum. The light chopper frequency was adjusted to a nominally 400-Hz chopping rate and the lock-in amplifier tuned to that frequency.

A drawing of a pneumatic probe-lowering assembly (constructed at NBS) is shown in figure 5. The system has four such assemblies. Each probe assembly contains two side-by-side spring-loaded probes (one is to carry the current for the photoinduced change in resistance measurement, the other to measure voltage). The pneumatic system assures that all eight probes are lowered simultaneously onto the surface of the slice. The entire pedestal assembly can move left or right in the figure. All four pedestals are equidistant from the center of the slice support and move in unison via a worm gear controlled by the system user. This permits automatic centering of the slice for measurement.

Drawings of the specimen holder (constructed at NBS) and its constituent parts including the pneumatic probe-lowering assembly are shown in figure 6. Except where noted, all parts are constructed of brass and the dimensions are given in inches.

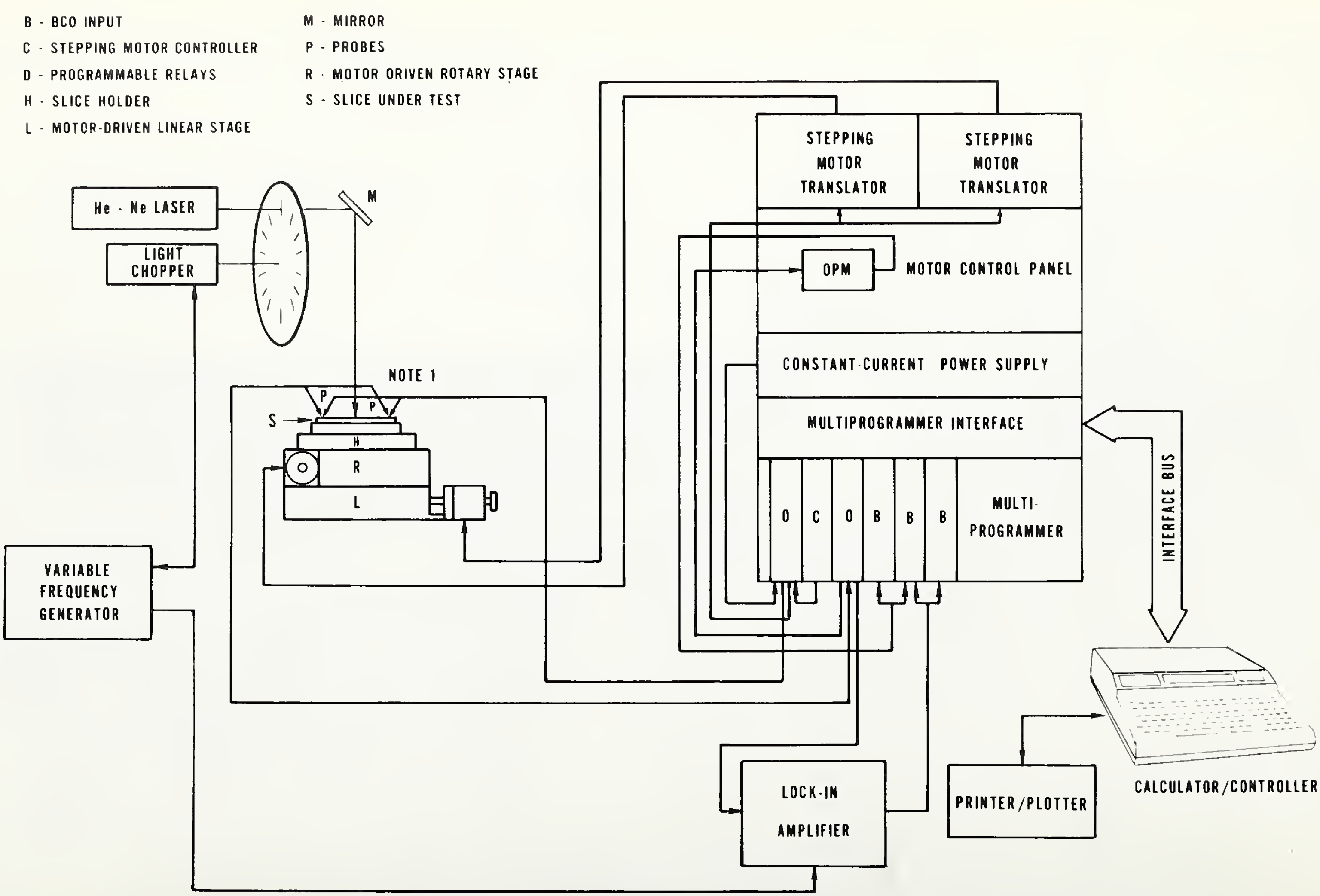
Figure 6a is a composite drawing top view and side view of the specimen holder. The front probe assembly has been removed for clarity in the side view. The circled numbers in the side view refer to the various



A - Calculator/Controller
B - Printer/Plotter
C - Multiprogrammer
D - Multiprogrammer Interface
E - Digital Panel Meter (DPM)
F - Stepping Motor Translators
G - Lock-In Amplifier
H - Helium-Neon Laser
J - Light Chopper
K - Mirror Assembly
L - Slice Holder
M - Motor-Driven Stage

a. Photograph of overall system.

Figure 1. Automated photovoltaic system for the measurement of resistivity variations in high-resistivity circular silicon slices.



NOTE 1: THE PROBES ARE ACTUALLY PERPENDICULAR TO THE SURFACE OF THE SLICE UNDER TEST

b. Diagram of system.

Table 1. Major Components of Photovoltaic System Obtained Commercially.

Item	Function	Features
Laser (Spectra Physics Model 124A)	To provide source of energy to generate electron-hole pairs.	He-Ne, $\sim$15-mW power at 0.6328-nm output
Lock-In Amplifier & Light Chopper (Princeton Applied Research Model 124)	Light chopper chops light at constant frequency and lock-in-amplifier monitors signal at that frequency. Permits low level ($\sim$1-μV) signals to be measured.	High input impedance (100-MΩ) differential preamplifier; sensitivity to 100-mV full scale; digital read-out; BCD output; programmable functions.
Linear & Rotary Motor Driven Stages (Aerotech Model ATS-303MM [linear] and ATS-301MR [rotary])	To translate slice to be measured beneath laser probe and to permit rotation of slice.	Total linear travel, 85 mm; linear resolution, 0.01 mm; linear bidirectional repeatability, 0.005 mm; rotational resolution, 2 arc minutes; rotational bidirectional repeatability, 0.2 arc minutes.
Multiprogrammer (Hewlett Packard Model 6940B)	Distributes instructions from controller to instruments, acquires data and multiplexes it to the computer/controller.	Part of the computer/controller system; compatible with IEEE Standard Digital Interface for Programmable Instruments — IEEE Std. 488-1975.
Computer/Controller (Hewlett Packard Model 9825A)	Controls systems, reduces data, controls printer/plotter to permit output of data.	Programmable; compatible with IEEE Std. 488-1975.
Printer/Plotter (Hewlett Packard Model 9871A)	To provide hard copy of measured resistivity profile.	Alphanumeric plotter; compatible with IEEE Std. 488-1975.
Digital Panel Meter (Newport Model 400AS)	To provide digital indication and output of voltage and current levels for van der Pauw measurement.	$\pm$399.9 mV full scale, 100-μV resolution.

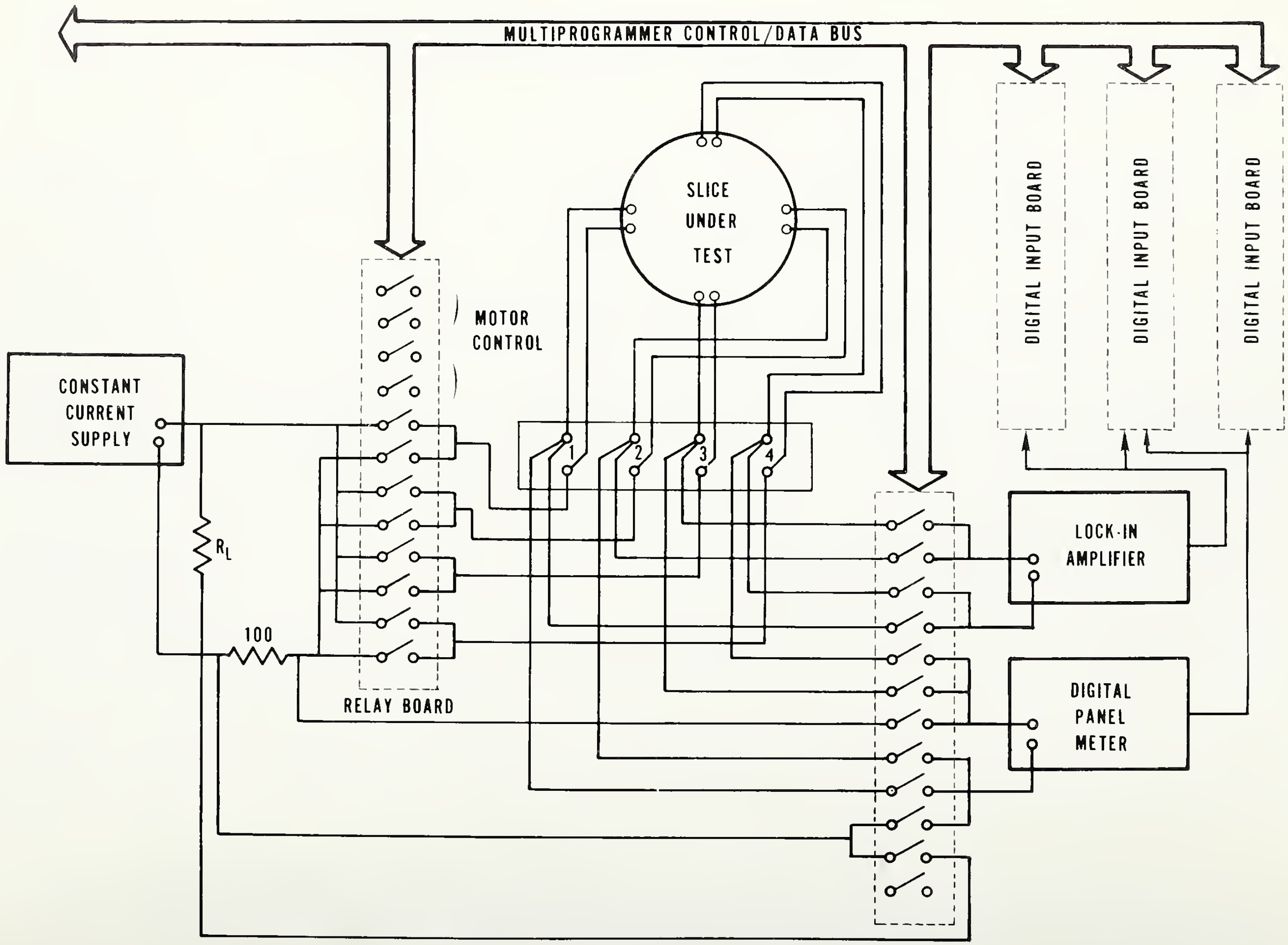


Figure 2. Electrical switching circuitry.

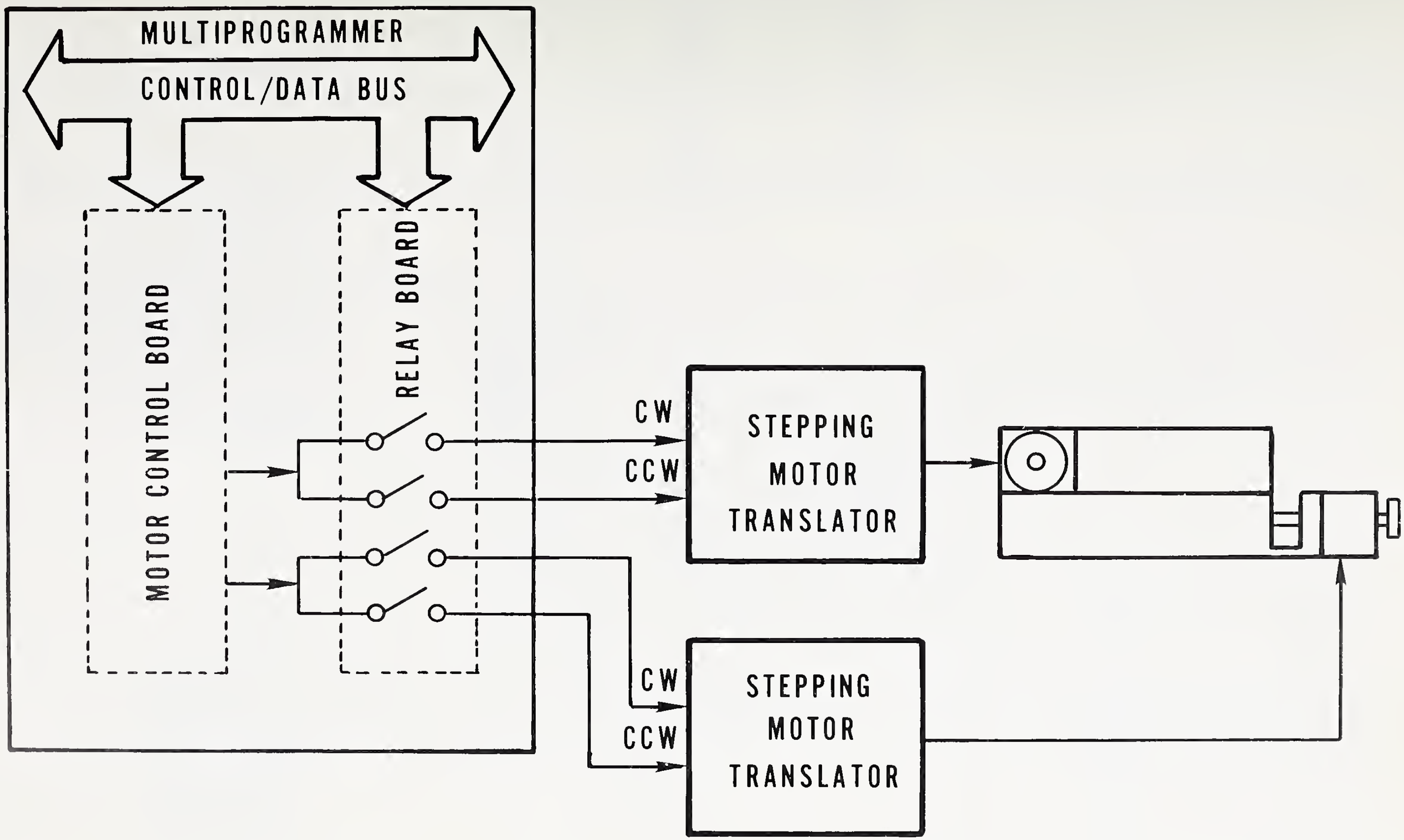


Figure 3. Motor-drive circuitry.

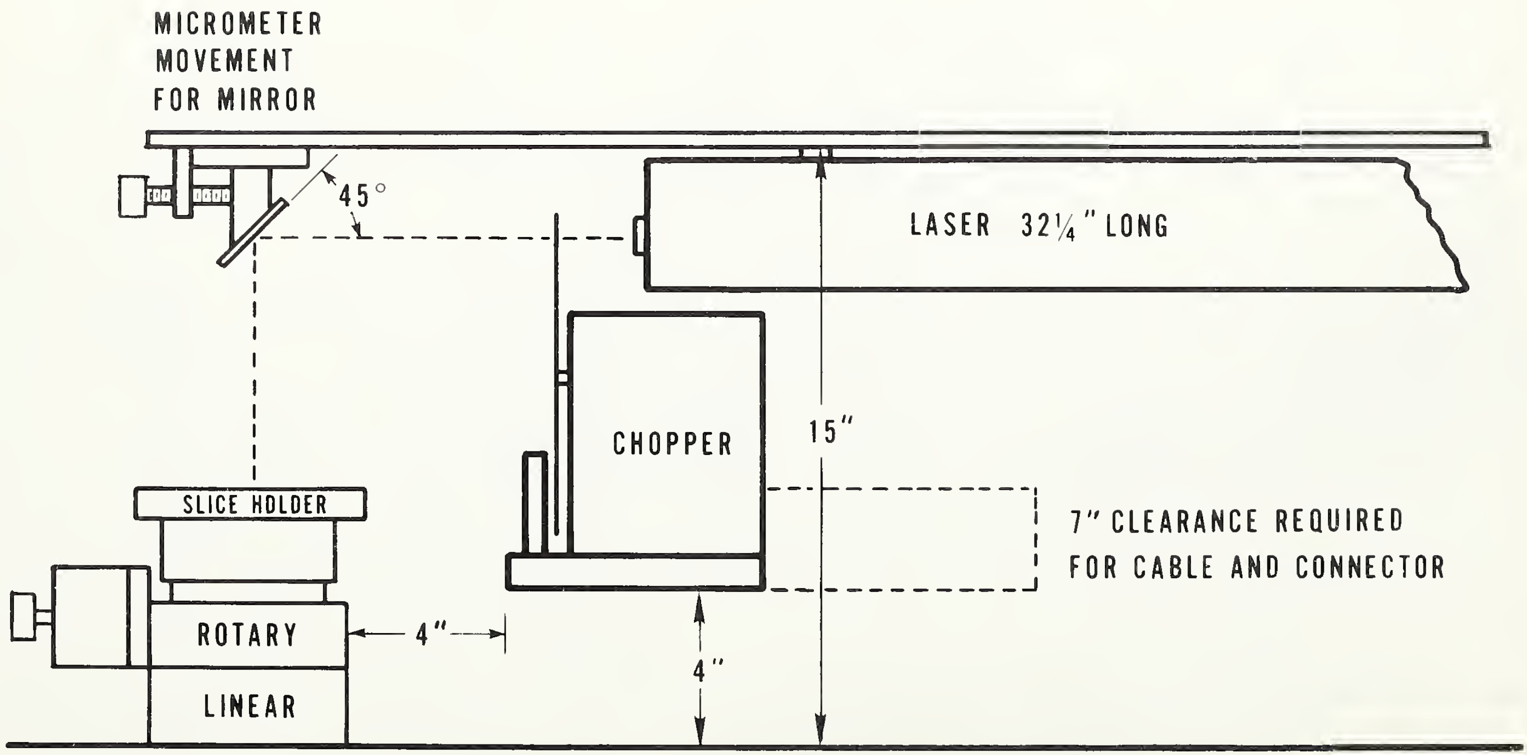


Figure 4. Laser support, light chopper, x-y stage, and mirror assembly. (Dimensions in the following figures given in inches.)

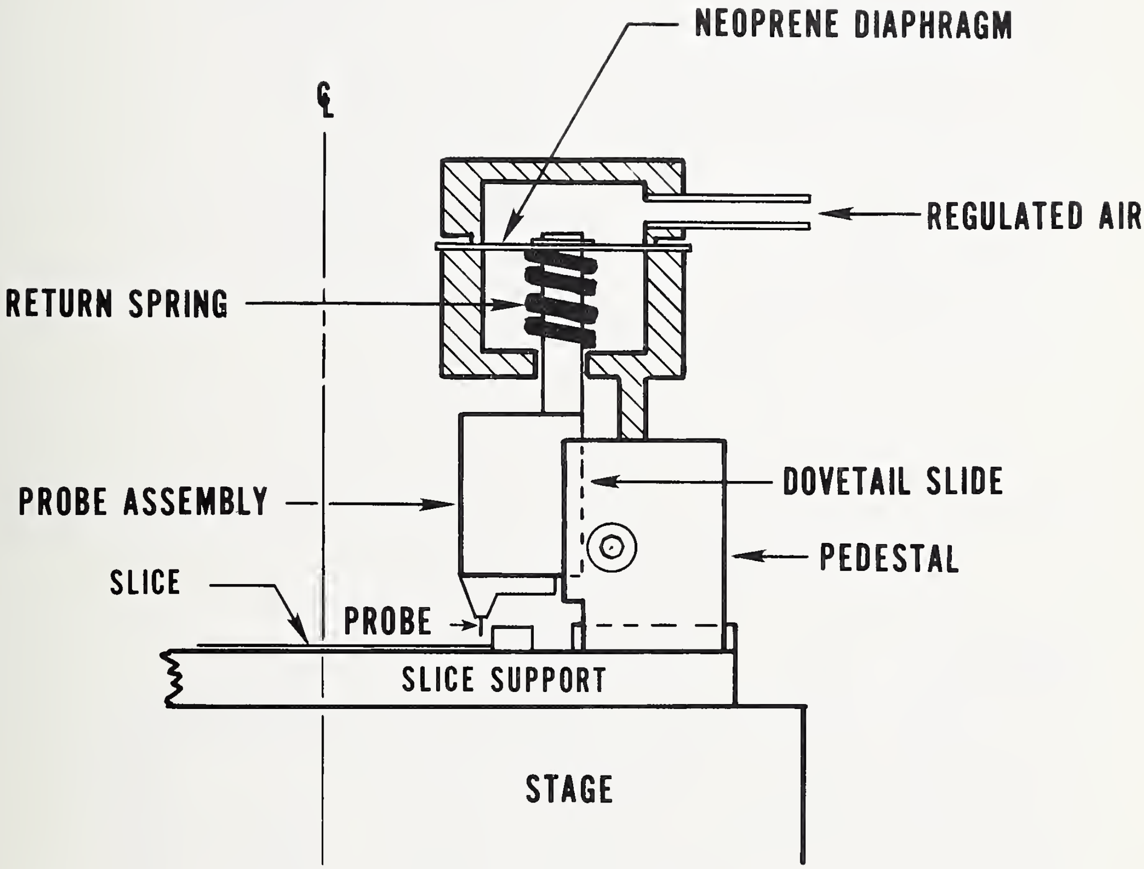


Figure 5. A pneumatic probe-lowering assembly.

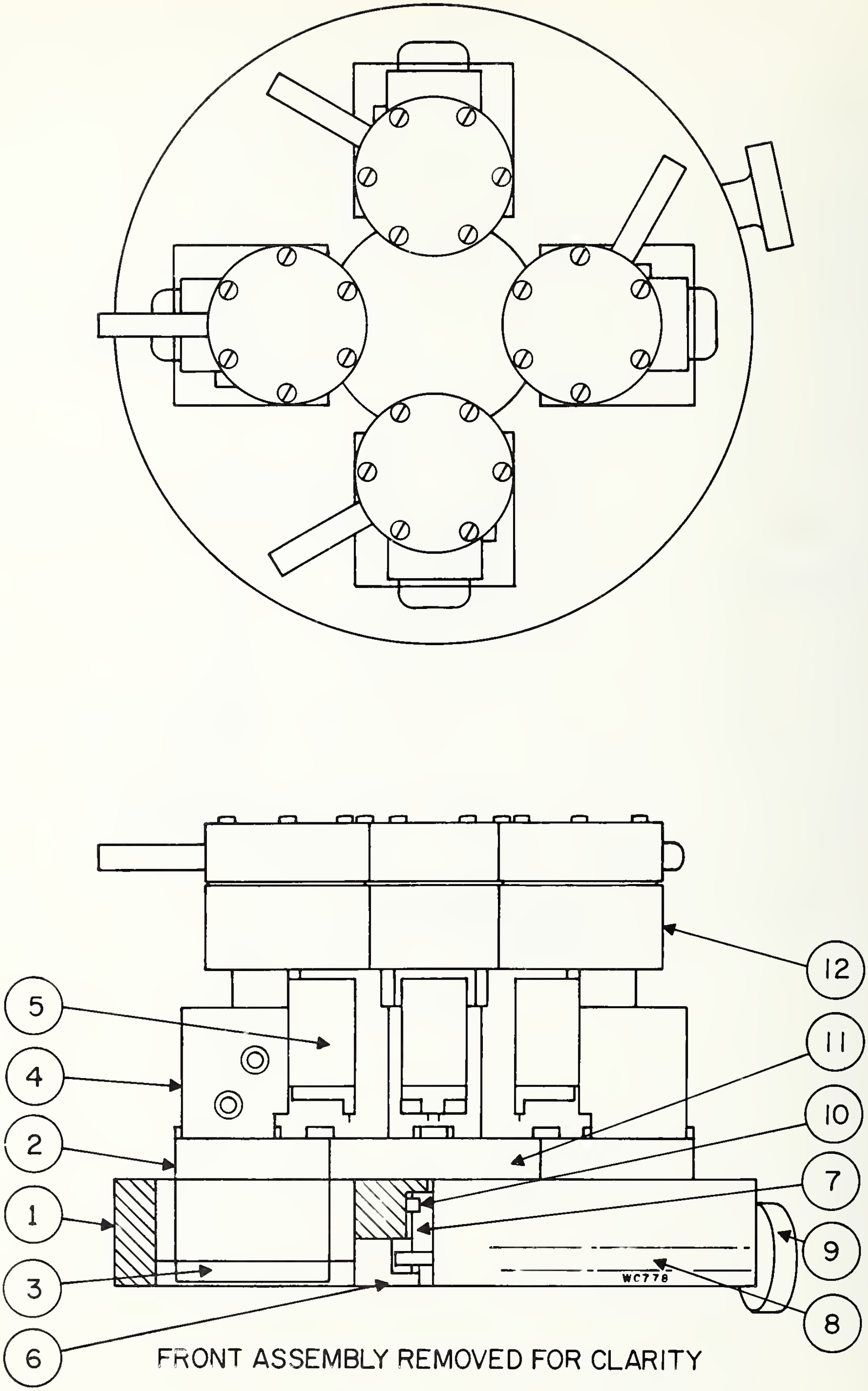


Figure 6a. Composite drawing of specimen holder.

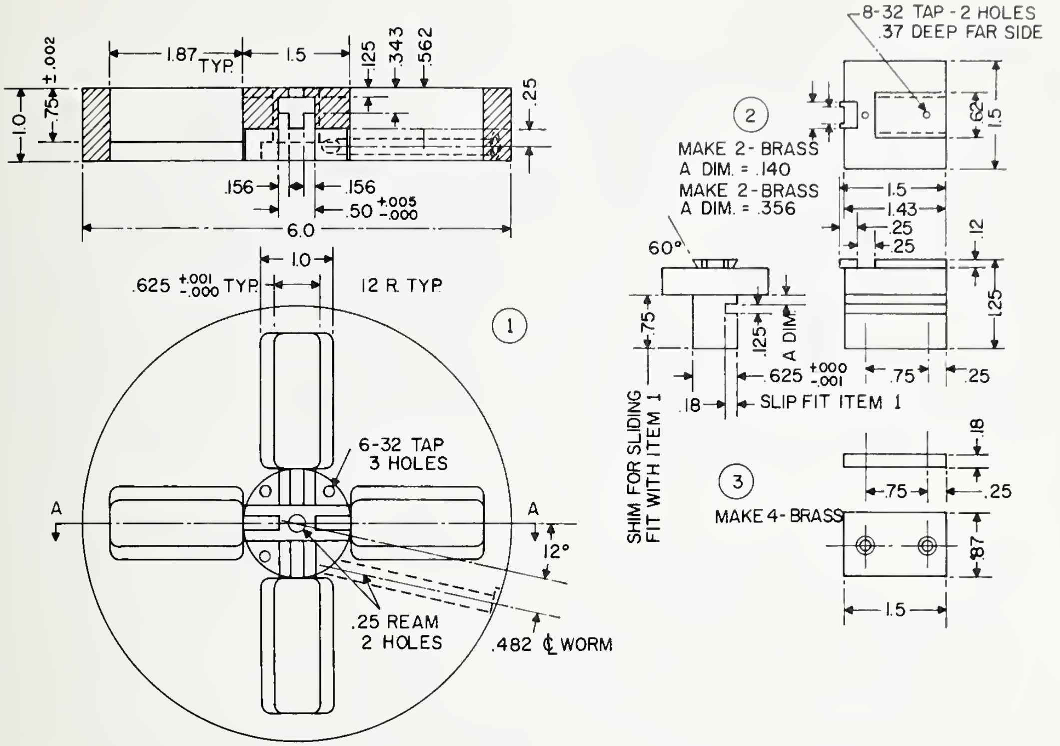


Figure 6b. Details of parts 1, 2, and 3 of the specimen holder.

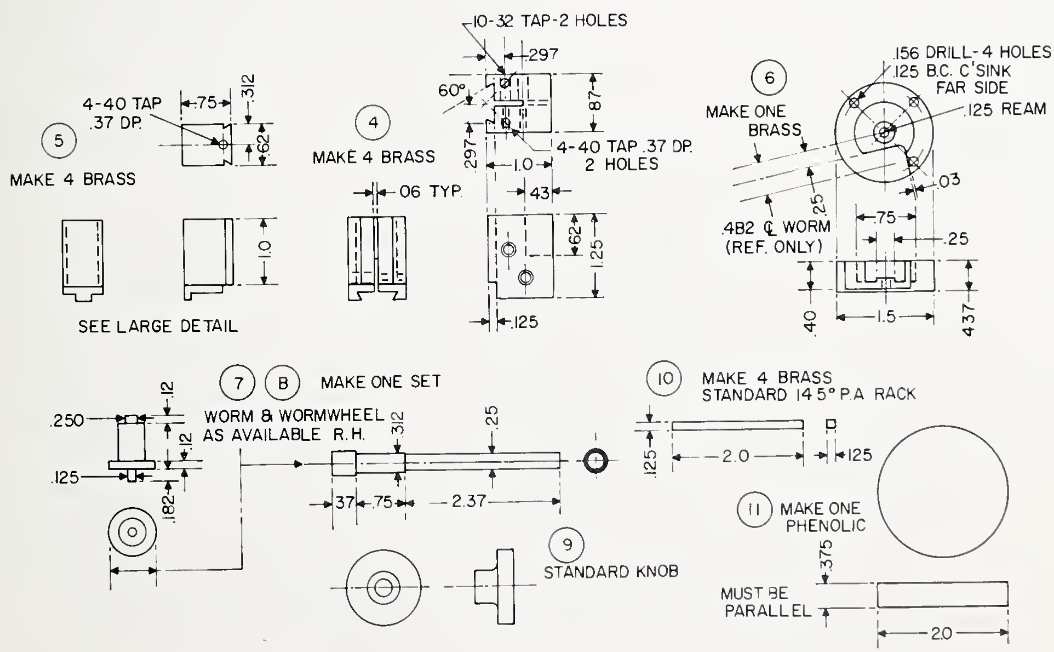


Figure 6c. Details of parts 4 through 11 of the specimen holder.

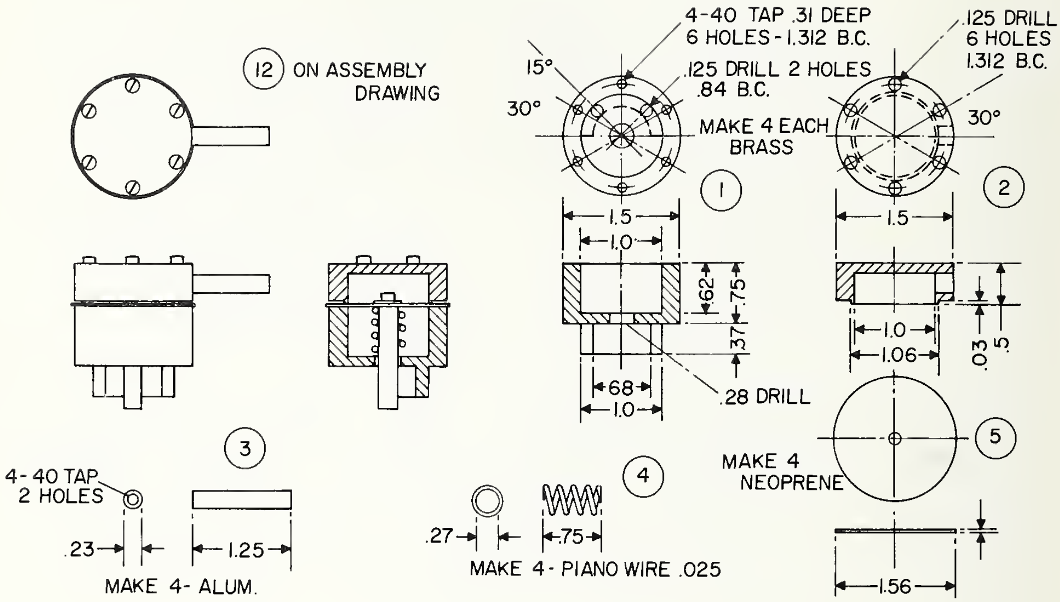


Figure 6d. Details of part 12 of the specimen holder.

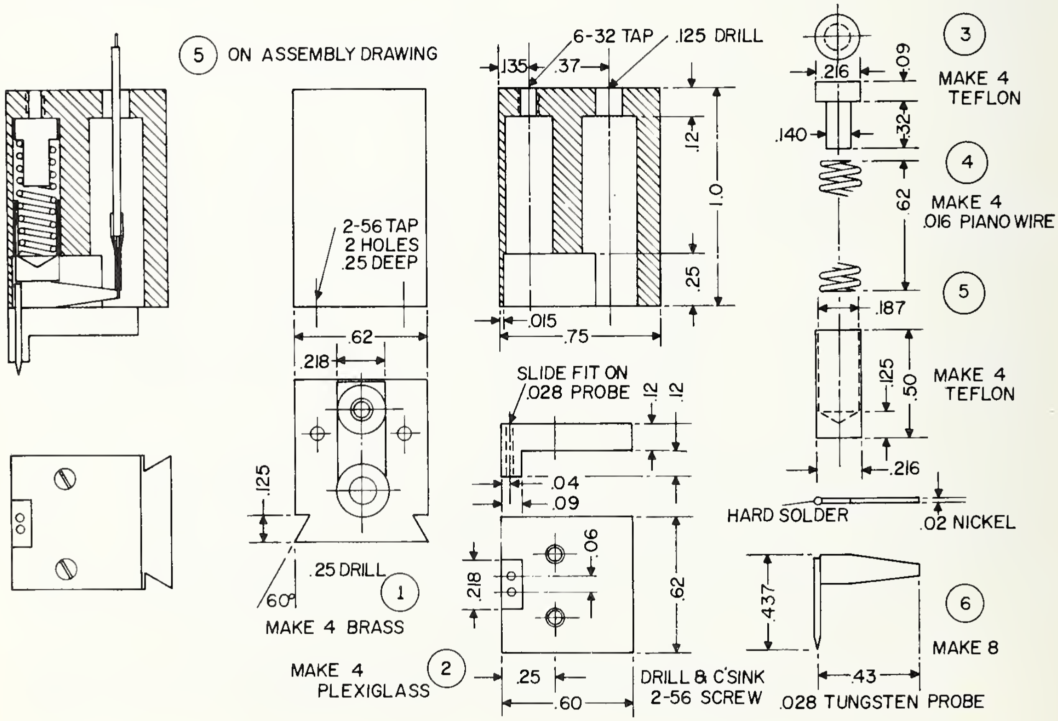


Figure 6e. Further details of probe assembly (part 5).

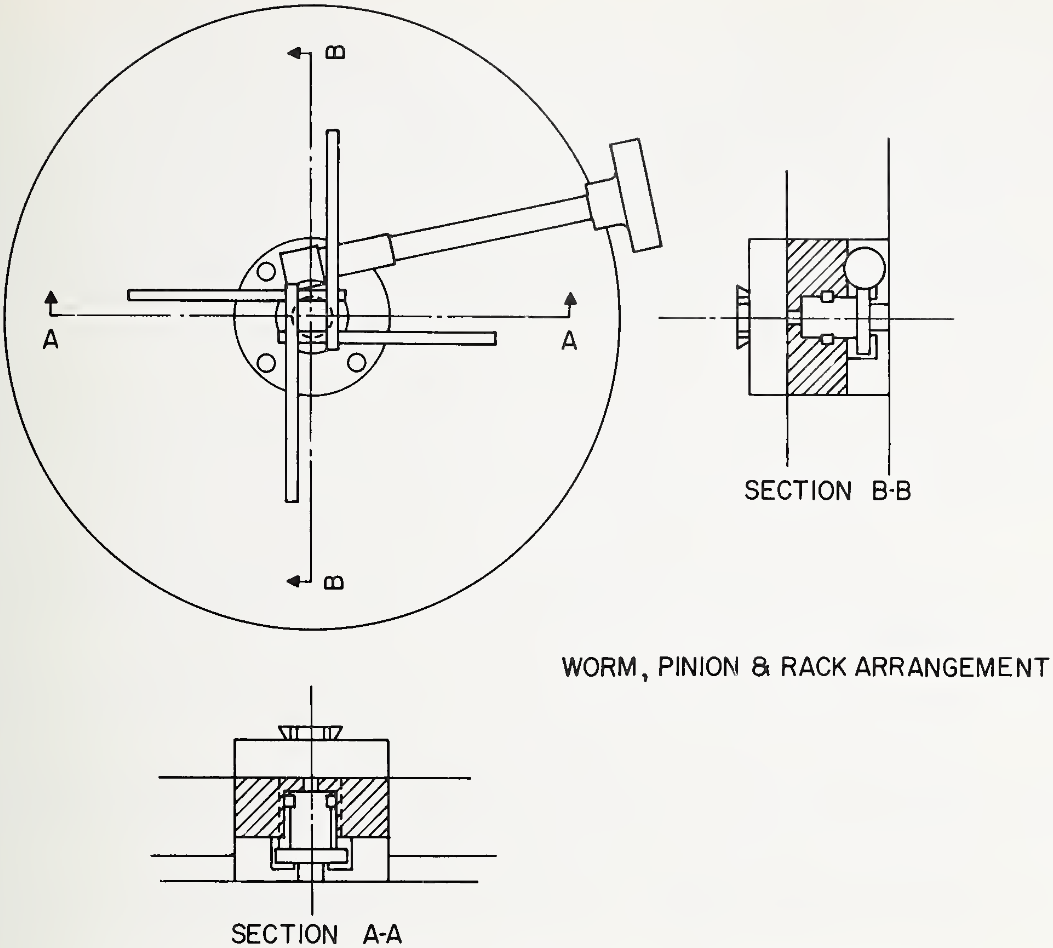


Figure 6f. Details of apparatus for centering slice.

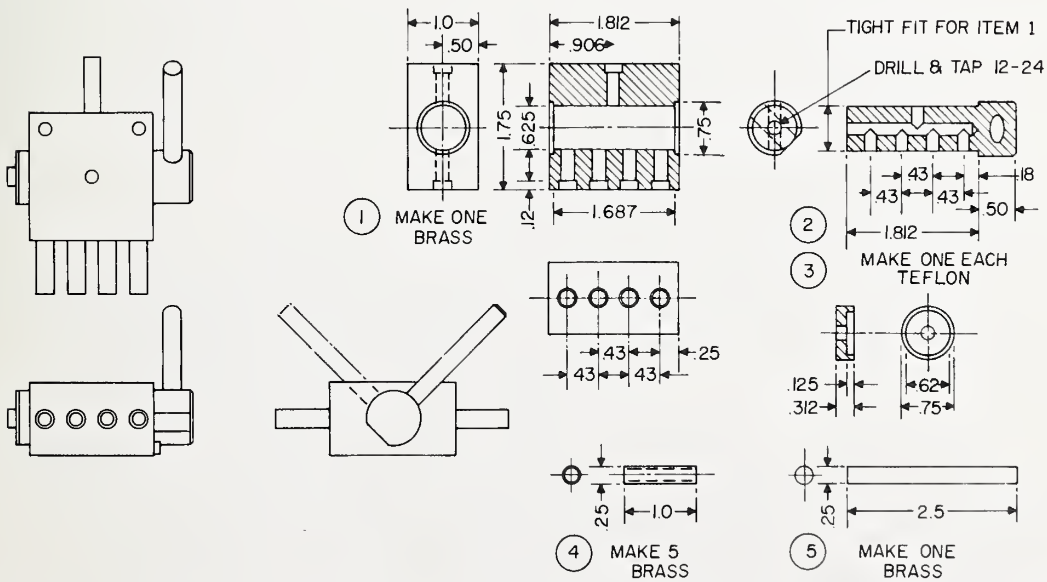


Figure 6g. Details for air distribution system for controlling pneumatic probe-lowering apparatus.

components for which detailed drawings follow. Figure 6b shows the details of parts 1, 2, and 3. Figure 6c shows details of parts 4 through 11. A drawing of part 12 is shown in figure 6d. The circled numbers 1 through 5 on this drawing refer to the various components of the assembly in this figure. In figure 6e, a further detailing of part 5 is shown. The circled numbers on this drawing also refer to the items of the assembly on the figure. The details of the worm, pinon, and rack arrangement for centering the slice are shown in figure 6f. Finally, the details of the air distribution valve which controls the air supplied to the pneumatic probe-lowering system (part 12) are shown in figure 6g.

3. SYSTEM OPERATION

The sequence of events for making a measurement of the resistivity gradient using the photovoltaic system is as follows:

1. The operator places the slice onto the specimen holder, turns the screw thread to bring in the probe assembly in unison to center the slice, and lowers the probes pneumatically onto the slice.

2. The operator loads the program to control the measurement (see Appendix B) into the memory of the computer.

3. The operator instructs the computer to start the measurement by depressing the start key on the computer.

4. The computer displays a series of messages asking for the following information:

   - specimen identification
   - date of measurement
   - time of measurement
   - specimen type (n or p)
   - slice diameter (cm)
   - slice thickness (cm)
   - slice average resistivity* (Ω·cm)
   - number of measurement points
   - distance between measurement points (cm)
   - lock-in amplifier time constant (s)
   - request if user desires to make a series of measurements on the slice center (where the light probe is located at the beginning) to assure that the proper time constant and sensitivity of the lock-amplifier is being used.

   The operator supplies all of the above information by typing the appropriate responses on the calculator keyboard. For produc-

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*See below for a procedure to obtain this quantity.

tion measurements, most of these responses could be stored in the computer memory before the measurement begins.

5. After the last response, the computer instructs the motor translator to move the specimen stage so that the light probe is at the end of the specimen diameter where the measurement is to begin.

6. The stage moves to the beginning point and the printer-plotter prints out the information on specimen identification, date, etc.

7. At the first measurement point, the computer instructs the stage to wait 10 lock-in amplifier time constants. After this time has passed, the lock-in amplifier is instructed to make a measurement and display the photovoltage measured at that point and to relay the value for storage in the computer.

8. The motors are instructed to move the stage to the next measurement point and wait 10 time constants. The lock-in amplifier is again instructed to display and relay its measurement. This sequence is repeated until all the specified number of measurements has been made.

9. When the light probe has reached the other end of the specimen diameter from which the measurement begins, the photovoltage scan is completed. The user is instructed by a display to turn on the constant current supply and to adjust it to the desired value (typically 1.0 mA for $10 \leq \rho \leq 60$ $\Omega\cdot$cm and 0.1 mA for $60 \leq \rho \leq 200$ $\Omega\cdot$cm).

10. The operator is asked by a displayed message if a one-time voltage sampling is again desired to assure the proper lock-in amplifier sensitivity is being used. Usually, the sensitivity is reduced by one to two orders of magnitude from that used for the photovoltage measurement to make the measurement of photoinduced change in specimen resistance.

11. After the proper sensitivity is selected, the measurement can begin. By depressing the continue key, the operator instructs the computer to begin the measurement. The measurements of the photoinduced change in specimen resistance are made at the same locations as were the photovoltage measurements, but the stage is traveling in the opposite direction. The motors are instructed to wait 10 time constants at each measurement position before a measurement is made.

12. When the light probe reaches the last point of the measurement, the computer begins calculating the resistivity variations at each point and performing the summation as described in section 3 of Appendix A. These results are listed by the printer-plotter. The resistivity is computed by adding a constant to

Table 2. Steps for the Measurement of Average Resistivity.

Step Number	Current Between Probes	Quantity Measured	Symbol
1	1+, 2−	Current	I_{12}
2	1+, 2−	Voltage between terminals 3 and 4	V_{34}
3	1−, 2+	Current	I_{21}
4	1−, 2+	Voltage between terminals 3 and 4	V_{43}
5	2+, 3−	Current	I_{23}
6	2+, 3−	Voltage between terminals 4 and 1	V_{41}
7	2−, 3+	Current	I_{23}
8	2−, 3+	Voltage between terminals 4 and 1	V_{14}

$$\bar{\rho} = 1.1331 \cdot t \cdot \left[\frac{V_{34} + V_{43}}{I_{21}} + \frac{V_{41} + V_{14}}{I_{23}} \right],$$

where t is the wafer thickness in cm.

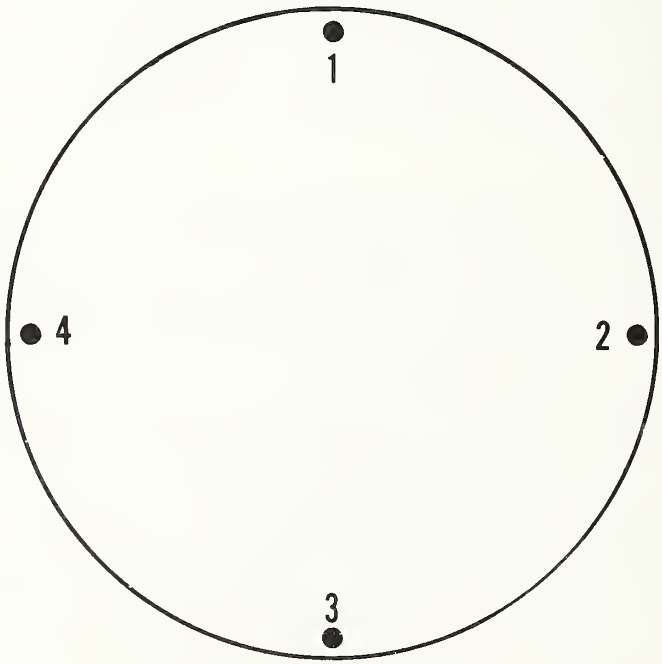

Figure 7. Slice geometry used for van der Pauw average-resistivity measurement.

each computer value so their average equals the van der Pauw average resistivity.

13. The computer then asks the operator via the display if a plot of resistivity *versus* position is desired. If so, the user changes paper and the plot is generated by the printer-plotter.

The system has also been programmed to measure the average specimen resistivity using the van der Pauw technique. If required, this measurement is performed between steps 1 and 2 above. The measurement sequence is:

1. The operator loads the van der Pauw measurement program into the memory of the computer.

2. The computer asks, via the display, what the specimen thickness (in cm) is. The answer is typed in by the user on the computer keyboard.

3. The computer tells the user, via the display, to turn on the constant current source and adjust it to the desired value, which is typically 0.1 mA.

4. The user instructs the computer to begin the measurement by pressing the start button. The measurement sequence is listed in table 2; the probes are identified by number in figure 7.

5. The computer calculates the average resistivity using the equation at the bottom of table 2.

Acknowledgments

The author thanks Mr. G. J. Rogers for his excellent efforts in assembling the automated system and in developing the required software, Dr. R. D. Larrabee for sharing his intuitive insights of the bulk photovoltaic effect and for his precise and in-depth analysis of the effect for circular slices, Mr. F. F. Oettinger for his many helpful discussions, Dr. W. M. Bullis for his critical reading of this manuscript, and Mr. W. A. Cullins for his craftsmanship in helping to design and in supervising the construction of the slice holder and mechanical supports.

4. REFERENCES

1. Oroshnik, J., and Many, A., Quantitative Photovoltaic Evaluation of the Resistivity Homogeneity of Germanium Single Crystals, *Solid-State Electronics* 1, 46-53 (1960).

2. Blackburn, D. L., Schafft, H. A., and Swartzendruber, L. J., Nondestructive Photovoltaic Techniques for the Measurement of Resistivity Gradients in Circular Semiconductor Wafers, *J. Electrochem. Soc.* 119, 1773-1778 (1972).

3. Blackburn, D. L., Photovoltaic Technique for Measuring Resistivity Variations of High Resistivity Silicon Slices, *J. Res. Nat. Bur. Stand.*, vol. 83, No. 3, 265-271 (May-June 1978).

4. Koyama, R. Y., Blackburn, D. L., and Oettinger, F. F., Measurement Techniques for High Power Semiconductor Materials and Devices, *Proc.: Light-Fired Thyristor Workshop*, EPRI Report WS-77-049, unpaged (March 1978).

5. Blackburn, D. L., and Larrabee, R. D., Automated Photovoltaic Technique for Nondestructively Measuring Resistivity Variations of High-Resistivity Silicon Wafers, *Semiconductor Characterization Techniques*, Proceedings Volume 78-3, P. A. Barnes and G. A. Rozgonyi, Eds, pp. 168-179 (The Electrochemical Society, Princeton, 1978).

6. Oettinger, F. F., Ed, Measurement Techniques for High Power Semiconductor Materials and Devices: Annual Report, January 1 to December 31, 1977, NBSIR 78-1474 (May 1978).

7. Larrabee, R. D., and Blackburn, D. L., Theory and Application of a Nondestructive Photovoltaic Technique for the Measurement of Resistivity Variation in Circular Semiconductor Slices (to be published).

JOURNAL OF RESEARCH of the National Bureau of Standards
Volume 83, No. 3, May-June 1978

Photovoltaic Technique for Measuring Resistivity Variations of High Resistivity Silicon Slices*

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January 13, 1978

A description of an automated, photovoltaic system for measuring the resistivity variation of high resistivity, large diameter silicon wafers is given. The photovoltaic technique utilizes a scanning light spot to induce a bulk photovoltage and a change in resistance from which is calculated the local variation in resistivity. This nondestructive technique requires no contacts to the useful fabrication area of the wafer, and measured results have good correlation with the results of the four-probe technique. Specific examples of measured resistivity gradients are presented along with a discussion of the theory, measurement conditions and limitations, and description of a calculator-based automated system to perform the measurements.

Key Words: Automation; computer control; homogeneity; measurement method; photovoltage, bulk; power semiconductor materials; resistivity; semiconductors; silicon; thyristors; transistors, power.

1. Introduction

The radial variation of resistivity is one of the principal characteristics specified in the procurement of silicon for the manufacture of high power semiconductor devices. Resistivity variations result from an inhomogeneous doping density in the starting silicon and both the solid state diffusion and alloying steps used in the fabrication of high power devices are affected by such inhomogeneities.

Gross variations in resistivity can cause wide variations in device characteristics and contribute to poor device yields. Poor junction geometry and nonuniform current distributions are frequent problems in devices fabricated from inhomogeneous material. Failures due to hot spots or thermal runaway may result. Also, localized low resistivity regions of a wafer limit operating voltage of a device fabricated from that wafer to values lower than those expected from the remainder of the wafer.

The method commonly used for determining the resistivity variations of starting silicon wafers is the four-probe technique. There are a number of difficulties and limitations with this method. A basic limitation in the application of this method to the measurement of resistivity variations is the relatively large sampling region of the probe [1].[1] Because of this, it has been recommended that to obtain better spatial resolution, a two-probe measurement be made along a narrow bar cut from along the measurement diameter of interest [2]. There can also be large errors introduced into the four-probe measurement due to slight mislocations of the probes, particularly near the wafer edge [1, 3]. The spreading resistance technique has none of these difficulties, but it can be very slow and time consuming. Perhaps the greatest limitation of any probing method such as spreading resistance or four-probe is the placement of probes onto the wafer surface in precisely those areas where diffusions and other processing steps are to occur. The damage caused by the probes may itself be detrimental to the reliability and yield of devices fabricated in these slices.

The photovoltaic technique offers an alternative for measuring resistivity variations along the diameter of circular wafers. The technique, which is based upon the theory of Tauc [4], requires no contact with the wafer surface in the area where a finished device or devices are to be fabricated. The validity of a modified photovoltaic theory for circular wafers was demonstrated several years ago [5]. The present work has established the feasibility of automating the photovoltaic technique for the rapid measurement of radial resistivity variations in high-resistivity, large-diameter, power grade silicon.

2. Theory of the Photovoltaic Effect

The underlying theory of the bulk photovoltaic effect was derived and its physical aspects discussed by Tauc [4]. The bulk photovoltaic effect is a phenomenon which occurs when electron-hole pairs are photogenerated in a region of an impurity-density gradient (or, equivalently, a resistivity gradient). In such a region, an internal electric field exists in the semiconductor. This is much like the situation at a *pn* junction, except that the field is much smaller than for a junction. When excess electron-hole pairs are generated in this region, they are separated by the internal electric field, and the steady-state distribution of the separated carriers is such that the magnitude of the net internal field is reduced. It is the reduction in magitude of the internal field which results in the photovoltage which can be measured at contacts made to the specimen. It is possible to relate this measured photovoltage to the resistivity gradient in the region where the excess electron-hole pairs are distributed.

The physics of the photovoltaic effect in one dimension is described graphically in figure 1. Figure 1a is a representation of a typical radial resistivity profile found in high-resistivity Czochralski-grown silicon. Figure 1b shows the band structure for such a resistivity variation and illustrates

* This work was conducted as part of the NBS program on Semiconductor Measurement Technology and was funded principally by the Energy Research and Development Administration, Divisions of Administration and Electrical Energy Systems, trhough ERDA Task Order A021-EES.

[1] Figures in brackets indicate literature references at the end of this paper.

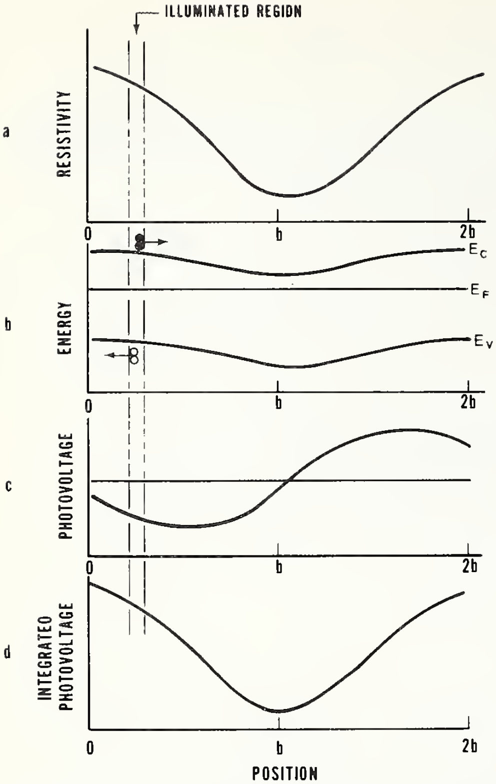


FIGURE 1. *A representation of (a) a typical resistivity profile, (b) the associated energy band structure, (c) photovoltage, and (d) integrated photovoltage for an n-type specimen.*

how the internal field (as manifested by the variation with position of the conduction and valence band edges) causes the photogenerated electron-hole pairs to be physically separated. Thus, a local voltage dipole is created. This results in a voltage measurable at the ends of the specimen. If the light is scanned along the specimen, a voltage profile can be determined, as shown in figure 1c. If this voltage is integrated over position, assuming that the steady-state excess density of photogenerated carriers is independent of position, and then multiplied by a constant dependent only upon known material parameters, one obtains the profile in figure 1d. This profile is identical to the variation in resistivity, as shown in figure 1a. Because the entire profile in figure 1d is shifted by an unknown integration constant, this method determines the variation in resistivity and not the absolute resistivity at each position. It will be shown later that a measurement of a weighted average specimen resistivity using the van der Pauw technique [6] can be employed to estimate the absolute resistivity at each position from the photovoltaic resistivity variation profile.

For most specimens, the excess density of steady-state photogenerated carriers is not constant with position. This is principally because the effective lifetime of the material is not constant but varies with position. This effect is accounted for in this measurement technique by also measuring the photoinduced change in specimen resistance as a function of position.

For circular specimens, where a small light spot falls on a wafer diameter and the photovoltage is measured at the ends of that diameter, the measured voltage also depends upon the position of the light spot on the diameter. The equation relating the resistivity variation to the photovoltage and photoinduced change in specimen resistance for a circular semiconductor wafer is:

$$\frac{d\rho}{dx} = \frac{q}{\pi kT} \frac{\left(1 + \dfrac{\mu_M}{\mu_m}\right)}{1 - (x/b)^2} \frac{\bar{\rho}^2}{bt} \frac{V(x)}{\Delta R(x)} \tag{1}$$

where b and x are shown in figure 2 and

$\dfrac{d\rho}{dx}$	= resistivity gradient ($\Omega \cdot$cm/cm)
q	= majority carrier charge (C)
k	= Boltzmann's Constant (J/K)
T	= temperature (K)
μ_M	= majority carrier mobility ($cm^2/V \cdot s$)
μ_m	= minority carrier mobility ($cm^2/V \cdot s$)
$\bar{\rho}$	= average resistivity ($\Omega \cdot$cm)
t	= thickness (cm)
$V(x)$	= photovoltage (V)
$\Delta R(x)$	= photoinduced change in resistance (Ω)

Equation (1) differs from the equation for $d\rho/dx$ derived previously [5] by a multiplicative factor of 4/3. In the course of this work, a more exact analysis of the effect of the circular geometry upon the measured photovoltage and photoinduced change in specimen resistance has shown that eq (1) is a better approximation for $d\rho/dx$ than that presented previously.

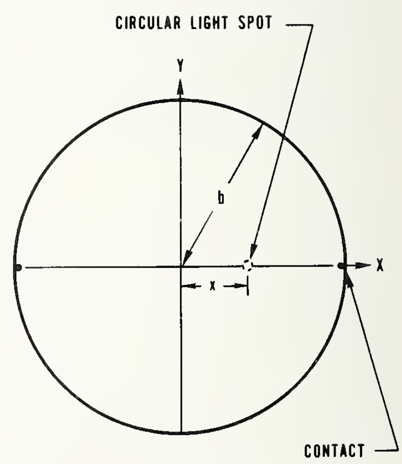


FIGURE 2. *The wafer geometry upon which eq (1) is based.*

3. Measurement Procedure

To measure the resistivity gradient using the photovoltaic technique, the circuit shown in simplified form in figure 3 is used. First, the photovoltage, $V(x)$, is measured as a function

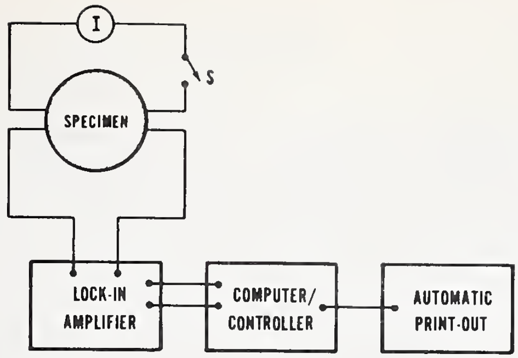
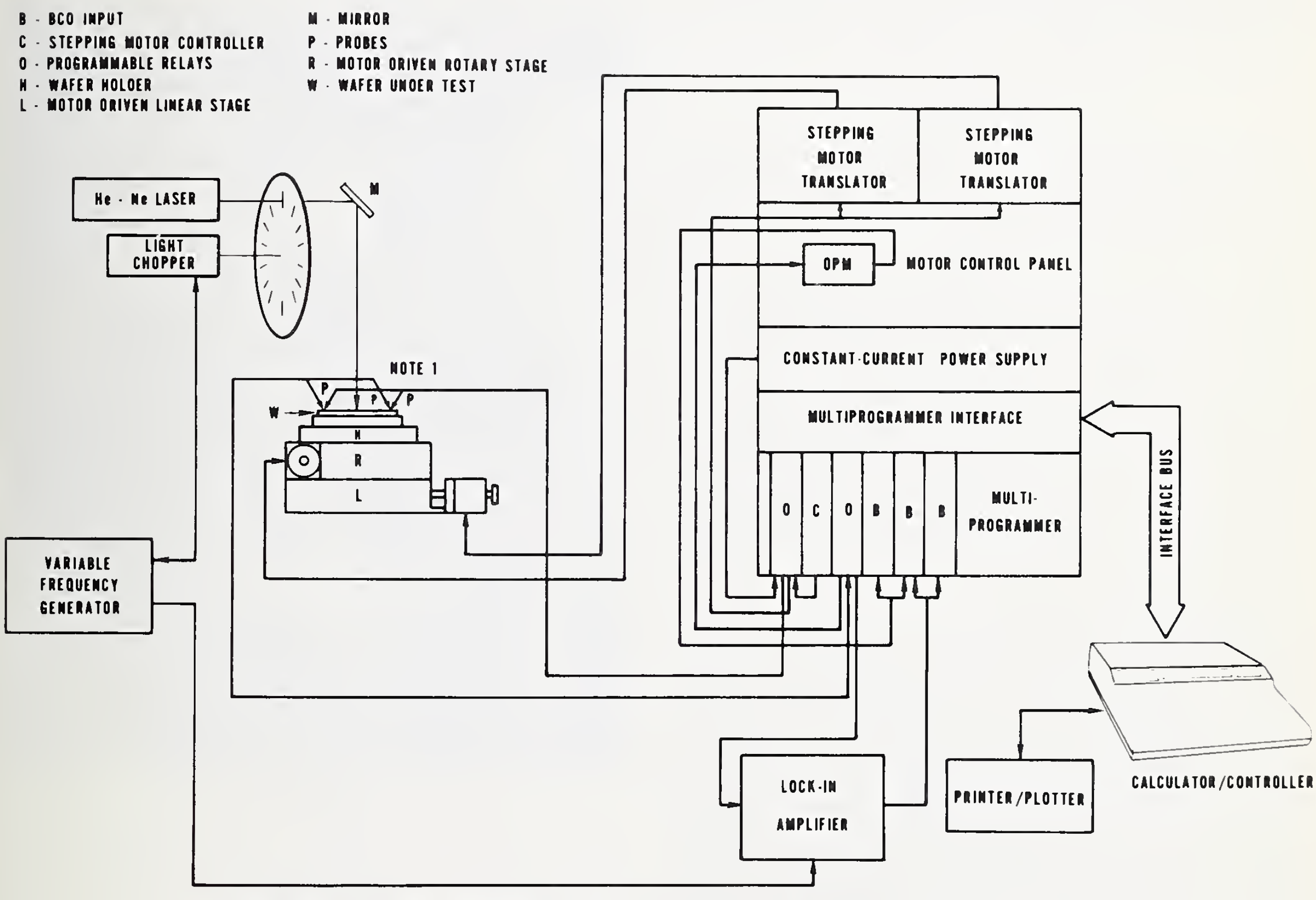


FIGURE 3. *Simplified version of the measurement system.*



NOTE 1: THE PROBES ARE ACTUALLY PERPENDICULAR TO THE SURFACE OF THE WAFER UNDER TEST.

FIGURE 4. *Schematic of automated measurement system.*

of position. This is done by having the switch S open, stepping the wafer beneath the light probe in constant increments, Δx, and measuring $V(x)$ at each position.

Next, the photoinduced change in specimen resistance, $\Delta R(x)$, is measured. This is accomplished by closing switch S and again stepping the wafer beneath the light probes in increments of Δx such that each $\Delta R(x)$ is measured at the same positions as $V(x)$. Because a constant current, I, exists in the specimen with the switch closed, a decrease in the voltage across the specimen occurs as the light sweeps along the diameter. This is because the total specimen resistance is decreased due to the localized decrease in resistivity caused by the excess electron-hole pairs generated by the light. If the change in voltage is $\Delta V(x)$, then:

$$\Delta R(x) = \frac{\Delta V(x)}{I}. \quad (2)$$

The quantities $V(x)$ and $\Delta R(x)$ are then inserted in eq (1) to compute the gradient, $d\rho/dx$, at each position, x. To determine the variation in ρ, the plot of $d\rho/dx$ is numerically summed ($\rho_m(x) = \sum_{i=1}^{m} (d\rho/dx)_i \Delta x$). Thus, a plot of the variation in resistivity is obtained. As mentioned, an absolute determination of resistivity is not obtained, but each $\rho_m(x)$ above differs from the absolute value by a constant, ρ_0, the value of the resistivity at the position the summation was begun. To estimate the value of ρ_0, the average of all the $\rho_m(x)$'s ($\rho_{mAVG} = 1/N \sum_{m=1}^{N} \rho_m(x)$) is subtracted from the measured van der Pauw average resistivity, $\bar{\rho}$ [6]. This value for ρ_0 is then added to each $\rho_m(x)$ to determine the absolute resistivity profile. The van der Pauw average resistivity measurement has been automated and is an intrinsic part of the measurement system.

4. Apparatus

A schematic of the automated photovoltaic measurement system is shown in figure 4. The entire measurement system is under the control of a computer/controller. The results of the measurements are furnished in hard copy by the printer/plotter.

He Ne Laser—A laser, operating at 0.6328-μm wavelength, is used as the source for generating the electron-hole pairs in the silicon. The laser used in this work has about a 15-mW power output at 0.6328 μm. The laser can also be operated at 1.152 μm with >2 mW of power output. It has been found, however, that the internal reflections within the silicon at this longer, very penetrating, wavelength can induce a barrier photovoltage at the measurement contacts which masks the bulk photovoltage generated at the light spot position. The 0.638-μm radiation is all absorbed very near the silicon surface and so is not reflected internally to the contact region. The laser is used because of the high energy density easily obtained within a small spot about 1 mm in diameter.

Lock-in Amplifier—The magnitude of the photovoltage is usually very small. In this work, for specimens with resistivity between 50 and 200 $\Omega\cdot$cm, the voltage is of the order of ± 1 μV. For specimens with resistivity between 10 and 50 $\Omega\cdot$cm, the photovoltage is of the order of ± 0.01 μV. To allow measurement of these small signals, the laser radiation is chopped mechanically with a light chopper and a lock-in amplifier used to measure the voltage. The chopping frequency is nominally 400 Hz. The frequency should be as high as possible while assuring the radiation stays on the specimen long enough during each cycle for the photovoltage to reach a steady-state value.

Motor Driven Stage—The specimen is held in a specimen holder (see next paragraph) which rests on a stepper-motor driven stage. The stepper motors are under control of the computer and are typically stepped so that measurements are made at 1-mm intervals.

Specimen Holder—A picture of the specimen holder is shown in figure 5. The holder is constructed so that measurement contact is made to the specimen on the top surface within about 1 mm of the rim. Contact is made at four locations at 90-deg increments around the wafer (on perpendicular diameters) in a van der Pauw arrangement [6]. At each contact location, two probes (similar to those used for spreading resistance or four-probe measurements) make contact with the wafer and are separated by about 1.5 mm.

The loading of each of the probes has been approximately 1.0 to 1.5 N in this work. During measurement of the bulk photovoltage, one of the probes at each end of the diameter being scanned is used to measure the voltage. During the measurement of the photoinduced change in specimen resistance, the other two probes (one at each end) are used to carry the constant current, and the change in potential across the specimen is measured with the same two probes as were used to measure the bulk photovoltage. Contact is made on perpendicular diameters to permit the measurement of the average specimen resistivity ($\bar{\rho}$) by the van der Pauw technique.

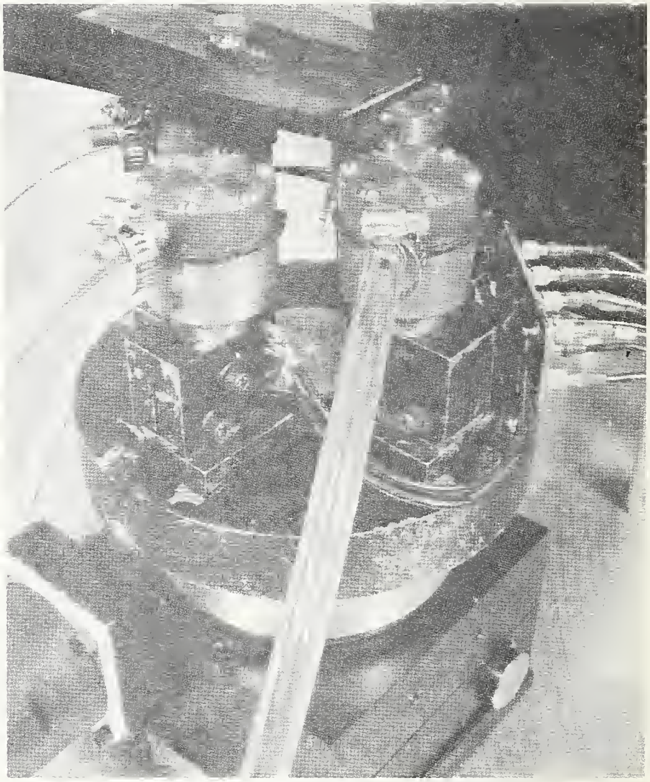


FIGURE 5. *Picture of specimen holder.*

5. Results

Two comparisons between the resistivity profiles as determined by the photovoltaic technique and by the four-probe method will be given to show the qualitative agreement that can be obtained. The comparisons are for high resistivity (~150 $\Omega\cdot$cm) and lower resistivity (~10 $\Omega\cdot$cm) specimens. The surfaces of the wafers were lapped with 12-μm alumina. Measurements have been made on polished surfaces, but these measurements were not as reproducible as those made on lapped surfaces.

In figure 6 is shown a comparison between the respective resistivity profiles as determined for a nominal 150 $\Omega\cdot$cm ,

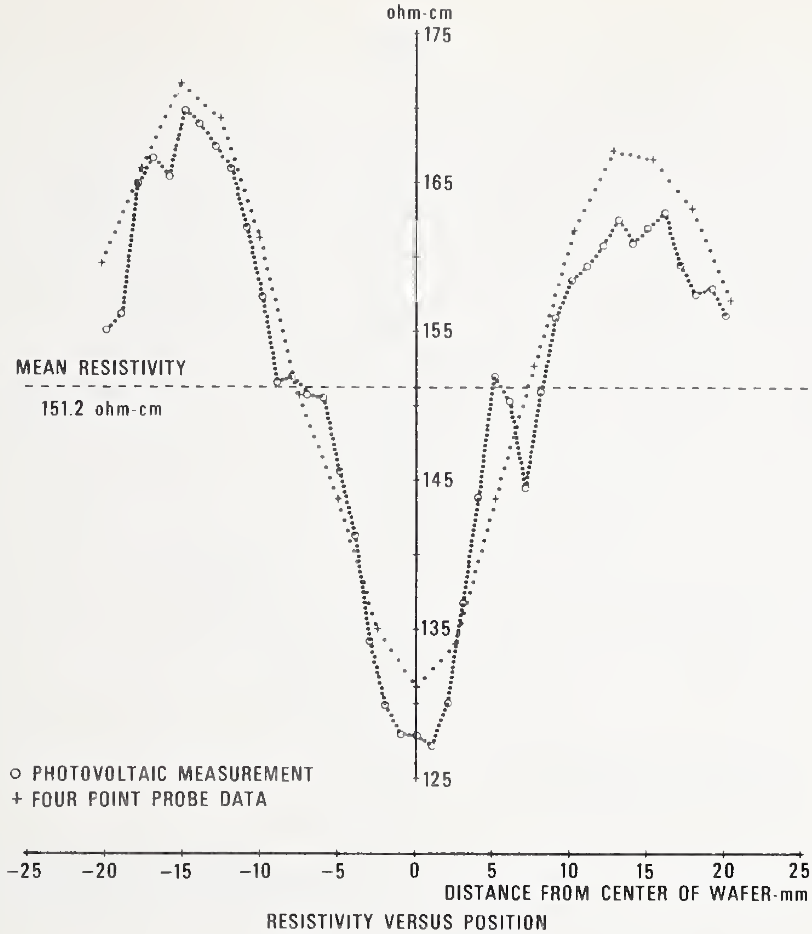


FIGURE 6. *Comparison of resistivity profiles as determined by the four-probe technique and the photovoltaic technique for a nominal 150 Ω·cm n-type silicon wafer.*

n-type silicon wafer. The total time required to determine the photovoltaic resistivity profile on the 5-cm diameter wafer was 2 to 3 min. The total time required for measurement depends upon the magnitude of the photovoltage, which was between -1 μV to 1 μV in this instance. The lock-in amplifier time constant was set to 100 ms and the light remained at each measurement point for about 20 time constants (i.e., ~2 s). Generally, for $\rho > 50$ Ω·cm, the 100-ms time constant has been found satisfactory.

For lower resistivity specimens, the signal level is usually smaller because of a decrease in $d\rho/dx$, and also perhaps because of a decrease in minority carrier life-time. Thus, the lock-in amplifier time constant must be increased and the measurement time increased. A comparison of photovoltaic and four-probe resistivity profiles for a nominal 10 Ω·cm n-type silicon wafer is shown in figure 7. The photovoltage for this specimen was usually in the range -0.01 μV to $+0.01$ μV. A 300-ms lock-in amplifier time constant was used and the total measurement time was about 8 min.

An indication of the reproducibility of the photovoltaic technique is given in figure 8. In this figure are shown the data for six resistivity profiles as determined by the photovoltaic technique along the same diameter of an n-type 135 Ω·cm silicon wafer. The measurements were made six different times over a period of several days. The wafer was removed and then reinserted into the specimen holder between measurements.

Detailed measurements to determine the spatial resolution of the photovoltaic technique have yet to be made. This will be done by comparing photovoltaic and spreading resistance resistivity profiles along the same wafer diameter. It is expected that the resolution will be one or two carrier diffusion lengths. In most high resistivity material, the diffusion length will be on the order of 0.5 to 1 mm. Thus, a spatial resolution of no better than 1 to 2 mm may be expected, regardless of light probe size.

The minimum resistivity gradient which can be measured depends upon a number of parameters. The more electron-hole pairs that are generated, the larger the signal for a given gradient and thus the smaller the minimum gradient measurable. Thus, the more intense the radiation source, the better the resistivity gradient resolution. Also, the longer the carrier lifetime, the better the resistivity gradient resolution (but the poorer the spatial resolution). In this work, the minimum gradient measurable has usually been of the order of 1.0 Ω·cm/cm (a 0.1 Ω·cm gradient over the 1-mm diameter light probe).

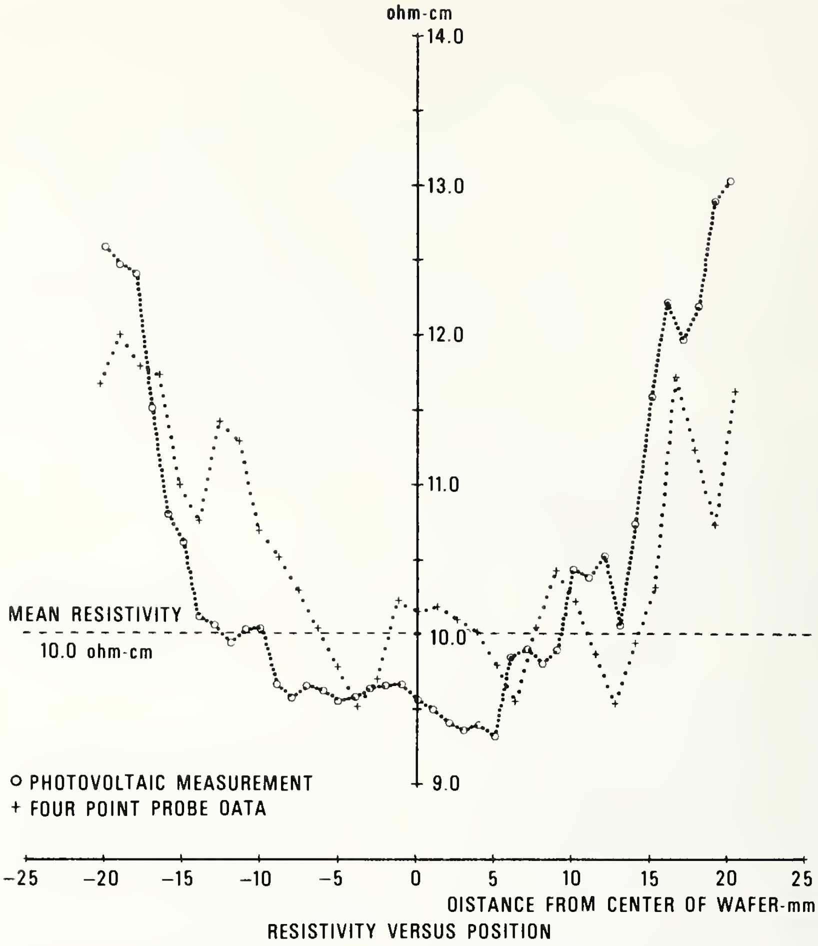


FIGURE 7. *Comparison of resistivity profiles as determined by the four-probe technique and the photovoltaic technique for a nominal 10Ω·cm n-type silicon wafer.*

Several photovoltaic resistivity measurements have been made on neutron transmutation doped (NTD) silicon. Because of the low resistivity gradients and the low lifetime usually present in this material, the bulk photovoltage has been extremely small; less than 0.01 μV. In addition, the presence of a front-to-back surface photovoltage interferes with the bulk photovoltage to such an extent that meaningful measurements on NTD material have not usually been possible. The front-to-back surface photovoltage is present on all specimens, but is only a problem when it is of the same order of magnitude as the bulk-photovoltage. This has been observed to be the case only in NTD silicon.

6. Conclusion

An automated system based upon the bulk photovoltaic effect for measuring the resistivity variations of high-resistivity power grade silicon has been described. A brief description of the theory of the photovoltaic effect was given. Comparisons between the resistivity profiles as determined using the new system and as determined by the four-probe technique have been given as well as an indication of the reproducibility of the photovoltaic technique. In the work described, the measurement of variations of about 0.1 Ω·cm for a 1-mm light probe diameter was possible. The spatial resolution of the technique is expected to be about 1 to 2 minority carrier diffusion lengths. The time of measurements is about 2 to 3 min for $\rho \geq 50$ Ω·cm and 8 to 10 min for $10 \leq \rho < 50$ Ω·cm.

The author gratefully acknowledges the contributions of R.D. Larrabee, G. J. Rogers and F. F. Oettinger to the results of this paper.

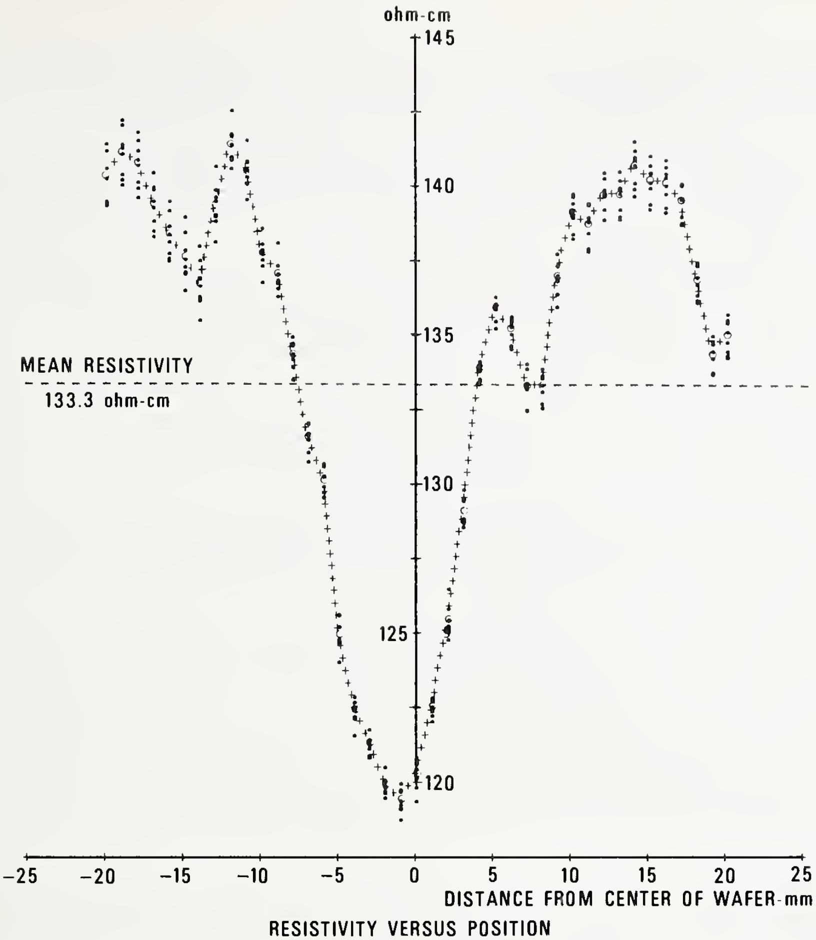


FIGURE 8. *Repetitive photovoltaic resistivity profiles made along the same diameter of an n-type silicon wafer.*

7. References

[1] Swartzendruber, L. J., Four-point probe measurement of non-uniformities in semiconductor sheet resistivity, *Solid-State Electronics* **7**, 413–422 (1964).

[2] Vieweg-Gutberlet, F., and Schönhofer, F. X., Grensen der anwendbarkeit des 4-spitzen-gleichstrom-messverfahrens an silicium-proben, Part I, *Arch. Tech. Messen.* **369**, 237–240 and Part II **370**, 259–262 (1966).

[3] Swartzendruber, L. J., Correction factor tables for four-point probe resistivity measurements on thin circular semiconductor samples, Natl. Bur. Std. (U.S.), Tech. Note 199, 34 pages (April 1964).

[4] Tauc, J., The Theory of a Bulk Photo-Voltaic Phenomenon in Semiconductors, *Czech. J. Phys.* **5**, 178–179 (1955).

[5] Blackburn, D. L., Schafft, H. A., and Swartzendruber, L. J., Nondestructive Photovoltaic Techniques for the Measurement of Resistivity Gradients in Circular Semiconductor Wafers, *J. Electrochem. Soc.* **119**, 1773–1778 (1972).

[6] van der Pauw, L. U., A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape, *Philips Res. Rept.* **13**, 1–9 (1958).

APPENDIX B

Typical Calculator/Controller Program for Measuring, Recording, and Plotting the Data Needed to Determine the Resistivity Variation of a Silicon Slice by the Photovoltaic Technique.

```
0: dim A$[1],B$[1],C$[8],D$[4],E$[12],F$[1],G$[3],H$[32]
1: ent "Date",C$,"Time",D$
2: ent "Wafer number",E$
3: ent "Wafer type [P or N]",F$
4: ent "Wafer diameter [cm]",D
5: ent "Wafer thickness [mm]",r1
6: ent "Wafer mean resistivity [ohm cm]",r2
7: ent "Label diameter (1-2,2-1,3-4,4-3)",G$
8: ent "Length of step [mm]",L
9: ent "Number of steps [even]",S
10: ent "How many readings to be averaged?",r3
11: ent "Amplifier time constant [msec]",T
12: ent "Store data in file number?",r12
13: 6→r0;0→I→M→Q→X→Y→Z→r8→r9;1→N;1000→J;100*L→A
14: if G$="1-2";4402→r10;3000→r11
15: if G$="2-1";3002→r10;3000→r11
16: if G$="3-4";222→r10;4400→r11
17: if G$="4-3";142→r10;4400→r11
18: ent "Plot 4-point probe data? (Y/N)",A$
19: if A$="N";jmp 14
20: dsp "INSERT DATA CARTRIDGE";beep;stp
21: ent "Number of data points",r8
22: dim G[r8+1],L[r8+1]
23: ent "Data file number",r9
24: if r8=17;1→r13
25: if r8=33;40→r13
26: if r8=35;62→r13
27: if r8=37;50→r13
28: if r8=41;63→r13
29: ldf r13,L[*];ldf r9,G[*];1→N
30: if G[N]>M;G[N]→M
31: if G[N]<J;G[N]→J
32: if (N+1→N)<r8+1;jmp -2
33: dsp "WAFER CENTERED?  LINEAR STAGE?";beep;stp
34: dim A[S+2],B[S+2],C[S+2],D[0:S+2],E[S+2],F[0:S+2]
35: dim J[S+2],K[S+2],M[r3+1],P[0:S+2]
36: fmt 1,c,f4.0,c,z;wrt 723.1,"O160T@",r11+31,"TO40T"
37: ent "Calibrate? (Y/N)",A$
38: if A$="Y";gsb "calibrate"
39: if A$="N";jmp 3
40: ent "Continue calibration? (Y/N)",B$
41: if B$="Y";jmp -3
42: 1→N;(N-1-S/2)*L→P[N];dsp "BEAM MOVING TO ´START´ POSITION"
43: 100*L*(S/2+1)→B;if B<4096;jmp 2
44: B-4095→B;7777→Y
45: dtoB→Z;fmt 1,c,z;wrt 723.1,"O160TG0002TO40T";gsb "motor"
46: fmt 1,c5,c10;wrt 6.1,"Date:",C$
47: fmt 1,c5,c7,c27;wrt 6.1,"Time:",D$,"WAFER"
48: fmt 2,c25,c11,c13,c3;wrt 6.2,"Number  :",E$,"Type     :",F$
49: fmt 3,c25,f6.2,c3,c15,f7.3,c3
*31690
```

0: reserves memory space for identifying data (date, slice number, etc.)
1-12: asks operator to enter slice identification and characteristics and conditions of test

13: assigns initial values to variables
14-17: selects current and voltage relays to correspond with diameter chosen in 7

18-32: provides for copying four-probe data from tape cassette

33: reminds the operator to center the slice and energize linear stage
34-35: reserves memory space for data

36: connects lock-in amplifier to diameter to be scanned
37-41: if the response is YES (Y in 37), triggers the meter at one-half second intervals for 15 seconds to permit selection of optimum meter range

42-45: moves stage to starting position

46-58: prints slice identification and characteristics and conditions of test

```
50: wrt 6.3,"Diameter:",D,"cm","Thickness:",r1,"mm"
51: fmt 4,c40,f8.3,c7;wrt 6.4,"Average resistivity:",r2,"ohm cm"
52: wrt 6
53: fmt 4,c41,c5;wrt 6.4,"Diameter       :",G$
54: fmt 5,c41,f6.2,c3;wrt 6.5,"Length of step :",L,"mm"
55: fmt 6,c41,f6.0;wrt 6.6,"Number of steps:",S
56: fmt 6,c41,f6.0,c3;wrt 6.6,"Time constant  :",T,"ms"
57: fmt 7,c58,f2.0;wrt 6.7,"Location of data file:  Track 1, file, ",r12
58: wrt 6;wrt 6
59: fmt 7,c11,c9,c21,c10,c6,c14,c11
60: fmt 8,c14,c11,c15,c10,c9,c11,c10
61: wrt 6.7,"Location","I=0","dR(x)","Sum(Rdx)","rho","dR´(x)","sum(R´dx)"
62: wrt 6.8,"[mm fm center]","Volts","Ohms","Ohm-cm","Ohm-cm","Ohms","Ohm-cm"
63: wrt 6
64: if F$="N";12.2427*3.6*r2*r2/(.05*D*r1)→r4
65: if F$="P";-12.2427*1.36*r2*r2/(.05*D*r1)→r4
66: fmt 1,c,z;wrt 723.1,"O160TG0001TO40T";gsb "step"
67: fxd 1;dsp "BEAM IS",P[N],"mm FROM CENTER";gsb "meter"
68: if J[N]=99;fmt 1,4x,f6.2,4x,c8;wrt 6.1,P[N],"OVERLOAD";jmp 2
69: fmt 2,4x,f6.2,5x,f6.3;wrt 6.2,P[N],A[N]
70: P[N]+L→P[N+1];if (N+1→N)<S+2;jmp -4
71: dsp "TURN CURRENT SUPPLY ON";beep;stp
72: fmt 1,c,f4.0,c,z;wrt 723.1,"O160TG",r10,"TO40T"
73: wrt 723.1,"O160T@0021TO40T"
74: dsp "ADJUST CURRENT";beep;stp
75: wtb 6,27,10;J[S/2]→r5;P[N]-L→P[N];N-1→N;ent "Current [mA]",Q
76: fmt 1,c,f4.0,c,z;wrt 723.1,"O160T@",r11+21,"TO40T"
77: ent "Calibrate? (Y/N)",A$
78: if A$="Y";gsb "calibrate"
79: if A$="N";jmp 5
80: ent "Continue calibration? (Y/N)",B$
81: if B$="Y";jmp -3
82: jmp 2
83: gsb "step"
84: fxd 1;dsp "BEAM IS",P[N],"mm FROM CENTER";gsb "meter"
85: if J[N]=99;fmt 1,22x,c8;wrt 6.1,"OVERLOAD";jmp 2
86: fmt 2,23x,f6.3;wrt 6.2,B[N]
87: wtb 6,27,10,27,10;P[N]-L→P[N-1];if (N-1→N)>=1;jmp -4
88: fmt 3,16x,"x10",f2.0,3x,"x10",f2.0
89: J[S/2]→r6;wrt 6.3,r5,r6
90: if r6<-5;wtb 6,27,10;fmt 3,c41,c29;wrt 6.3,"x10-3","x10-3"
91: wtb 6,27,10,27,10,27,10;fmt 4,22x,"I=",f5.3,"mA";wrt 6.4,Q
92: wtb 6,27,77,10,10;1→N;0→r7
93: fmt 1,c,z;wrt 723.1,"O160T@0021TO40T"
94: dsp "CHECK CURRENT";beep;beep;beep;wait 5000
95: -1*abs((B[S/2+1]*10^r6-A[S/2+1]*10^r5)/(.001*Q))→C[S/2+1]
96: -1*abs((B[N]*10^r6-A[N]*10^r5)/(.001*Q))→C[N]
97: 1/(1-(P[N]/(5*D))^2)→J[N]
98: C[N]/J[N]^2→K[N]
99: L/10*r4*J[N]*A[N]*10^r5/C[N]→D[N]
*11314
```

59-63: prints heading for data

64,65: calculates constants for *n*- and *p*-type material.

66-70: steps the stage through the number of positions prescribed in steps 8 and 9 of section 3 of this report, reads the meter at each position, and prints the position of the stage and photovoltage in two columns. If the meter overloads, prints the position of the stage and the word OVERLOAD.

71: instructs the operator to turn on the current supply

72-76: connects current supply to the diameter to be scanned, reads the current with the digital panel meter, instructs operator to adjust the current and enter the value, and connects the lock-in amplifier to the diameter to be scanned

77-82: if the response is YES (Y in 77), triggers the meter at one-half second intervals for 15 seconds to permit selection of optimum meter range

83-87: steps the stage through the same positions covered in 66-70 but in the reverse direction (the motor reversal was included in the value of r11 in 76), reads the meter at each position, and prints the photoinduced change in voltage in a third column, starting at the bottom of the column and moving up. If the meter overloads, prints the word OVERLOAD.

88-91: prints the multipliers for the photovoltage and photoinduced change in voltage columns and the value of the current

92: moves the printer to the first row of data and sets counter

93,94: disconnects the lock-in amplifier and directs the operator to read the current again

95-112: calculates the photoinduced change in specimen resistance and the change in resistivity for both the actual and idealized cases and prints these values in the next five columns

```
100: D[N]+D[N-1]→D[N]
101: if P[N]>=-16;if P[N]<=16;D[N]+r7→r7;R+1→R
102: L/10*r4*1/J[N]*A[N]*10^r5/C[S/2+1]→F[N]
103: F[N]+F[N-1]→F[N]
104: if (N+1→N)<S+2;gto 96
105: r2-r7/R→r7;D[S/2+1]+r7→E[S/2+1];1→N
106: D[N]+r7→E[N]
107: K[N]*(E[S/2+1]/E[N])^2→K[N]
108: if r6<-5;1000*C[N]→C[N];1000*K[N]→K[N]
109: fmt 1,32x,3f9.3,3x,f9.4,f9.3;wrt 6.1,C[N],D[N],E[N],K[N],F[N]
110: if E[N]>M;E[N]→M
111: if E[N]<J;E[N]→J
112: if (N+1→N)<S+2;jmp -6
113: wrt 723.1,"O160T@0031TO40T"
114: fmt 1,c,z;wrt 723.1,"O160TG0001TO40T"
115: dsp "BEAM RETURNING TO WAFER CENTER"
116: 100*L*S/2→C;0→X→Y→Z;if C<4096;jmp 2
117: C-4095→C;7777→Y
118: dtoC→Z;fmt 1,c,z;wrt 723.1,"O160TG0001TO40T";gsb "motor"
119: dsp "To plot, change paper in printer.";beep;stp
120: if r8>0;ent "PLOT FOUR-POINT PROBE DATA? (Y/N)",F$
121: fxd 2;dsp "Rmin=",J,"Rmax=",M,"Ymin=?";ent "",J
122: fxd 2;dsp "Rmin=",J,"Rmax=",M,"Ymax=?";ent "",M
123: cll ´form´(9.5,13,13)
124: cll ´psiz´(9.75,8,3,.5)
125: cll ´scl´(-26,25,J-(M-J)/5,M+(M-J)/10)
126: cll ´move´(-25,J-(M-J)/10);wait 1000
127: cll ´xaxis´(J-(M-J)/10,5,-25,25)
128: cll ´move´(0,J);wait 1000
129: cll ´yaxis´(0,(M-J)/10,J,M)
130: -25→I;fmt f3.0,z
131: cll ´move´(I,J-(M-J)/10);cll ´space´(-1);cll ´skip´(1)
132: wrt 6,I;if (I+5→I)<-5;jmp -1
133: cll ´move´(I,J-(M-J)/10);cll ´space´(-1);cll ´skip´(1)
134: fmt f2.0,z;wrt 6,I;if (I+5→I)<=25;jmp -1
135: cll ´space´(-32);cll ´skip´(1);wrt 6,"DISTANCE FROM CENTER OF WAFER-mm"
136: J→I;if r2<10;fmt 1,f5.2,z;jmp 3
137: if r2<100;fmt 1,f6.1,z;jmp 2
138: if r2>=100;fmt 1,f4.0,z
139: cll ´move´(0,I);wrt 6.1,I;jmp (I+(M-J)/5→I)>M
140: cll ´move´(-1.5,M);cll ´skip´(-1);wrt 6,"OHM-CM"
141: cll ´move´(P[1],E[1]);1→N;cll ´char´(46,5,3)
142: cll ´fplt´(P[N],E[N],111);jmp (N+1→N)>S+1
143: 25→N
144: cll ´plt´(N,r2,45);jmp (N-1→N)=-25
145: cll ´move´(-25,r2);cll ´skip´(-1);wrt 6,"MEAN RESISTIVITY"
146: cll ´skip´(1);fmt 1,7x,f6.2,c7,z;wrt 6.1,r2,"ohm-cm"
147: 1→N
148: if F$="Y";cll ´plt´(L[N],G[N],42);jmp (N+1→N)>r8
149: cll ´move´(-26,J);wrt 6,"o PHOTOVOLTAIC MEASUREMENT"
*31005
```

113-114: shorts current supply and reverses direction of stepping motor

115-118: returns laser beam to center of slice

119-122: determines if plots of resistivity and four-probe data are desired and requests operator to set abscissa limits

123-129: locates plot on page and draws x- and y-axes

130-135: scales and labels x-axis

136-140: scales and labels y-axis

141,142: plots resistivity, E(N), versus position, P(N), using the symbol o to locate the data points

143-146: plots the mean resistivity specified in 6 as a dashed line

147-148: plots four-probe data, G(N), versus position, L(N), using the symbol * to locate the data points

149,150: prints legend for plots

```
150: if F$="Y";cll 'move'(-26,J);cll 'skip'(1);wrt 6,"* FOUR POINT PROBE DATA'
151: cll 'move'(0,J);cll 'skip'(8);cll 'space'(-13)
152: wrt 6,"RESISTIVITY VERSUS POSITION"
153: cll 'move'(0,J);cll 'skip'(9);cll 'space'(-10);fmt c8,c12,14x,c8,c8
154: wrt 6,"WAFER: ",E$,C$,D$
155: cll 'move'(0,J);cll 'skip'(10);cll 'space'(-6);fmt c10,c3
156: wrt 6,"DIAMETER  ",G$
157: cll 'move'(0,J);cll 'skip'(11);cll 'space'(-16)
158: ent "Comment? (32 characters)",H$;fmt c32;wrt 6,H$
159: ent "Record data on cassette? (Y/N)",A$
160: if A$="Y";dsp "INSERT DATA CARTRIDGE";beep;stp
161: trk 1;rcf r12,E[*]
162: wtb 6,13;trk 0;dsp "END";beep;gto 119
163: "calibrate":
164: 0→I
165: wrt 723,"O260TAT240T";wait 500;jmp (I+500→I)=15000
166: 0→I;ret
167: "meter":
168: 1→I;0→P
169: fmt ;wait 10*T
170: wait 1*T
171: wrt 723,"O260TAT240TAT";red 723,E
172: wrt 723,"O240TCT";red 723,F
173: if E>=10000;E-10000→E;otdE→E;E-6int(E/16)-60int(E/256)→E
174: if F>=100;F-100*int(F/100)→F
175: if F>=40;99→J[N];gto 191
176: if F>=20;F-20→F;1→G;jmp 2
177: -1→G
178: if F>=10;F-10→F;1→K;jmp 2
179: 0→K
180: F-7→J[N]
181: G*(K+E/1000)→M[I]
182: M[I]+P→P;if (I+1→I)<=r3;gto 170
183: if r3=1;r3→r22;gto 189
184: P/r3→r20;1→I;0→P
185: (M[I]-r20)(M[I]-r20)+P→P;jmp (I+1→I)>r3
186: √(P/(r3-1))→r21;1→I;0→P→r22
187: if M[I]>=r20-2r21;if M[I]<=r20+r21;M[I]+P→P;r22+1→r22
188: if (I+1→I)<=r3;jmp -1
189: if Q=0;P/r22→A[N];jmp 2
190: P/r22→B[N]
191: ret
192: "motor":
193: fmt 3,c,f4.0,c,z;wrt 723.3,"O160TK",X,"TO40T"
194: wrt 723.3,"O160TK",Y,"TO40T"
195: wrt 723.3,"O160TK",Z,"TO40T"
196: ret
197: "step":
198: 0→X→Y;dtoA→Z;gsb "motor"
199: ret
*20643
```

151-158: prints title of graph and allows one additional line to enter additional information as a comment

159-161: provides for recording resistivity values on cassette if desired

162: end statement

163-166: "calibrate" subroutine triggers meter at one-half second intervals

166-191: "meter" subroutine

168-172: pauses and reads meter

173-181: converts BCD to decimal and separates overload and polarity information

182-186: takes r3 measurements, averages them, and determines the standard deviation

187,188: selects r22 measurements which are within two standard deviations of the mean

189,190: averages the measurements that are within two standard deviations of the mean and records photovoltage (A[N]) or photoinduced change in specimen voltage (B[N])

192-196: "motor" subroutine moves the linear stage X+Y+Z steps in the direction, and using the values for X, Y, and Z, determined by the main program

197-199: "Step" subroutine converts the length of step selected by the operator to an octal number and calls the "motor" subroutine

```
"form":
wtb r0,27,77
wtb r0,27,84
wtb r0,27,87,int(120*p1/64),120*p1
wtb r0,27,76,int(96*p2/64),96*p2
wtb r0,27,70,int(96*p3/64),96*p3
ret
"psiz":
p1→H;p2→W
wtb r0,27,79,int(p4*120/64),p4*120,int(p3*96/64),p3*96
ret
"scl":
120W/(p2-p1)→U
96H/(p4-p3)→V
p1→X;p3→Y
ret
"xaxis":
wtb 6,27,46,95,0,5,9
wtb 6,27,65,int((p3-X)U/64),int((p3-X)U),int((p1-Y)V/64),int((p1-Y)V)
p3→p5;wtb 6,43;wtb 6,8
wtb 6,27,114,int(p2U/64),int(p2U),0,0;wtb 6,43,8;jmp (p5+p2→p5)>=p4
ret
"yaxis":
wtb 6,27,46,124,0,3,0
wtb 6,27,65,int((p1-X)U/64),int((p1-X)U),int((p3-Y)V/64),int((p3-Y)V)
p3→p5;wtb 6,43;wtb 6,8
wtb 6,27,114,0,0,int(p2V/64),int(p2V);wtb 6,43,8;jmp (p5+p2→p5)>=p4
ret
"move":
wtb 6,27,65,int((p1-X)U/64),int((p1-X)U),int((p2-Y)V/64),int((p2-Y)V)
ret
"space":
if p1<0;gto +2
wtb r0,32;jmp 2((p1-1→p1)=0)
wtb r0,8;jmp (p1+1→p1)=0
ret
"skip":
if p1<0;gto +2
wtb r0,10;jmp 2((p1-1→p1)=0)
wtb r0,27,10;jmp (p1+1→p1)=0
ret
"plt":
wtb r0,27,65,int((p1-X)U/64),int((p1-X)U),int((p2-Y)V/64),int((p2-Y)V)
wtb r0,p3;wtb r0,8
ret
"fplt":
wtb 6,27,97,int((p1-X)U/64),int((p1-X)U),int((p2-Y)V/64),int((p2-Y)V)
wtb 6,p3;wtb 6,8
ret
"char":
if p2=0;5→p2;0→p3
wtb 6,27,46,p1,int(p2/64),p2,p3
ret
*1722
```

200-206: "form" subroutine sets dimensions of plotter page

206-210: "psiz" subroutine locates the graph on the page

211-215: "scl" subroutine scales the graph

216-221: "xaxis" subroutine draws the x-axis

222-227: "yaxis" subroutine draws the y-axis

228-230: "move" subroutine moves the plotter to position p1,p2

231-235: "space" subroutine moves the plotter horizontally

236-240: "skip" subroutine moves the plotter vertically

241-244: "plt" subroutine plots data points with no connecting lines

245-248: "fplt" subroutine plots data points and connects them by a line

249-252: "char" selects the character to be used to connect the data points

NBS-114A (REV. 9-78)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. SP 400-52	2. Gov't. Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE *Semiconductor Measurement Technology:* An Automated Photovoltaic System for the Measurement of Resistivity Variations in High-Resistivity Circular Silicon Slices	5. Publication Date November 1979 6. Performing Organization Code
7. AUTHOR(S) David L. Blackburn	8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, DC 20234	10. Project/Task/Work Unit No. 11. Contract/Grant No. ERDA Task Order A021-EES
12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)* Department of Energy Division of Electric Energy Systems Washington, DC 20545	13. Type of Report & Period Covered Final 12/75 - 10/77 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 79-600178

[X] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report describes an automated photovoltaic system for nondestructive measurement of resistivity variations of high-resistivity circular silicon slices. The computer-based system for making the measurements is described, detailed construction diagrams are given to facilitate reproduction of the system, and a listing of the computer program for controlling the system is given. Comparisons between resistivity profiles determined using the automated photovoltaic system and the four-probe technique indicate that the photovoltaic system is adequate for production screening and incoming inspection of high-resistivity float-zoned silicon slices.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Automation; bulk photovoltaic effect; computer control; homogeneity; measurement method; nondestructive testing; photoconductivity; power devices; resistivity variation.

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01. Summary date (Yr. / Mo. / Day)	
02. Summary prepared by *(Name and Phone)*	David L. Blackburn
03. Summary action	New [X] Replacement [ ] Deletion [ ]
Previous Internal Software ID	
04. Software date (Yr. / Mo. / Day)	
05. Software title	Automated Photovoltaic System
06. Short title	
07. Internal Software ID	PVI
08. Software type	[X] Automated Data System; [ ] Computer Program; [ ] Subroutine/Module
09. Processing mode	[X] Interactive; [ ] Batch; [ ] Combination
10. Application area — General	[ ] Computer Systems Support/Utility; [X] Scientific/Engineering; [ ] Bibliographic/Textual; [ ] Management/Business; [ ] Process Control; [ ] Other
Application area — Specific	

11. Submitting organization and address

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Center for Electronics & Electrical Engineering
National Engineering Laboratory
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13. Narrative

This software controls an automated photovoltaic system for measuring resistivity variations of circular semiconductor slices. The software is used with an HP 9825A calculator/controller, controls a system using the IEEE Standard 488-1975 interface bus, and gives hardcopy output via a printer. The software requires about 9000 bytes of storage and uses Hewlett Packard's version of BASIC.

14. Keywords

Automated measurement; nondestructive; resistivity variation; silicon slices.

15. Computer manuf'r and model	16. Computer operating system	17. Programing language(s)	18. Number of source program statements
Hewlett Packard 9825A	Photovoltaic	Hewlett Packard BASIC	252

19. Computer memory requirements	20. Tape drives	21. Disk/Drum units	22. Terminals
9000 bytes 8 bits/byte	One - integral to HP 9825A	0	One - integral to HP 9825A

23. Other operational requirements

Printer/plotter (HP 9871A), Multiprogrammer (HP 6940B)

24. Software availability			25. Documentation availability		
Available [X]	Limited [ ]	In-house only [ ]	Available [X]	Inadequate [ ]	In-house only [ ]

26. FOR SUBMITTING ORGANIZATION USE

Standard Form 185
1974 July
U.S. Dept. of Commerce—NBS
(FIPS. Pub. 30)

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