ASTM
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Standard Test Methods for
Measuring Resistivity and Hall Coefficient and Determining Hall Mobility in Single-Crystal Semiconductors[1]

1. Scope

1.1 These test methods cover two procedures for measuring the resistivity and Hall coefficient of single-crystal semiconductor specimens. These test methods differ most substantially in their test specimen requirements.

1.1.1 *Test Method A, van der Pauw* (1) [2]—This test method requires a singly connected test specimen (without any isolated holes), homogeneous in thickness, but of *arbitrary* shape. The contacts must be sufficiently small and located at the periphery of the specimen. The measurement is most easily interpreted for an isotropic semiconductor whose conduction is dominated by a single type of carrier.

1.1.2 *Test Method B, Parallelepiped or Bridge-Type*—This test method requires a specimen homogeneous in thickness and of *specified* shape. Contact requirements are specified for both the parallelepiped and bridge geometries. These test specimen geometries are desirable for anisotropic semiconductors for which the measured parameters depend on the direction of current flow. The test method is also most easily interpreted when conduction is dominated by a single type of carrier.

1.2 These test methods do not provide procedures for shaping, cleaning, or contacting specimens; however, a procedure for verifying contact quality is given.

NOTE 1—Practice F418 covers the preparation of gallium arsenide phosphide specimens.

1.3 The method in Practice F418 does not provide an interpretation of the results in terms of basic semiconductor properties (for example, majority and minority carrier mobilities and densities). Some general guidance, applicable to certain semiconductors and temperature ranges, is provided in the Appendix. For the most part, however, the interpretation is left to the user.

1.4 Interlaboratory tests of these test methods (Section 19) have been conducted only over a limited range of resistivities and for the semiconductors, germanium, silicon, and gallium arsenide. However, the method is applicable to other semiconductors provided suitable specimen preparation and contacting procedures are known. The resistivity range over which the method is applicable is limited by the test specimen geometry and instrumentation sensitivity.

1.5 The values stated in acceptable metric units are to be regarded as the standard. The values given in parentheses are for information only. (See also 3.1.4.)

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.7 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D1125 Test Methods for Electrical Conductivity and Resistivity of Water

E2554 Practice for Estimating and Monitoring the Uncertainty of Test Results of a Test Method Using Control Chart Techniques

F26 Test Methods for Determining the Orientation of a Semiconductive Single Crystal (Withdrawn 2003)[4]

F43 Test Methods for Resistivity of Semiconductor Materials (Withdrawn 2003)[4]

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F47 Test Method for Crystallographic Perfection of Silicon by Preferential Etch Techniques[4]
F418 Practice for Preparation of Samples of the Constant Composition Region of Epitaxial Gallium Arsenide Phosphide for Hall Effect Measurements (Withdrawn 2008)[4]

2.2 *SEMI Standard:*
C1 Specifications for Reagents[5]

3. Terminology

3.1 *Definitions:*

3.1.1 *Hall coefficient*—the ratio of the Hall electric field (due to the Hall voltage) to the product of the current density and the magnetic flux density (see X1.4).

3.1.2 *Hall mobility*—the ratio of the magnitude of the Hall coefficient to the resistivity; it is readily interpreted only in a system with carriers of one charge type. (See X1.5)

3.1.3 *resistivity—of a material*, is the ratio of the potential gradient parallel to the current in the material to the current density. For the purposes of this method, the resistivity shall always be determined for the case of zero magnetic flux. (See X1.2.)

3.1.4 *units*—in these test methods SI units are not always used. For these test methods, it is convenient to measure length in centimetres and to measure magnetic flux density in gauss. This choice of units requires that magnetic flux density be expressed in V·s·cm^{-2} where:

$$1 \text{ V·s·cm}^{-2} = 10^8 \text{ gauss}$$

The units employed and the factors relating them are summarized in Table 1.

4. Significance and Use

4.1 In order to choose the proper material for producing semiconductor devices, knowledge of material properties such as resistivity, Hall coefficient, and Hall mobility is useful. Under certain conditions, as outlined in the Appendix, other useful quantities for materials specification, including the charge carrier density and the drift mobility, can be inferred.

5. Interferences

5.1 In making resistivity and Hall-effect measurements, spurious results can arise from a number of sources.

5.1.1 Photoconductive and photovoltaic effects can seriously influence the observed resistivity, particularly with high-resistivity material. Therefore, all determinations should be made in a dark chamber unless experience shows that the results are insensitive to ambient illumination.

5.1.2 Minority-carrier injection during the measurement can also seriously influence the observed resistivity. This interference is indicated if the contacts to the test specimen do not have linear current-versus-voltage characteristics in the range used in the measurement procedure. These effects can also be detected by repeating the measurements over several decades of current. In the absence of injection, no change in resistivity should be observed. It is recommended that the current used in the measurements be as low as possible for the required precision.

5.1.3 Semiconductors have a significant temperature coefficient of resistivity. Consequently, the temperature of the specimen should be known at the time of measurement and the current used should be small to avoid resistive heating. Resistive heating can be detected by a change in readings as a function of time starting immediately after the current is applied and any circuit time constants have settled.

5.1.4 Spurious currents can be introduced in the testing circuit when the equipment is located near high-frequency generators. If equipment is located near such sources, adequate shielding must be provided.

5.1.5 Surface leakage can be a serious problem when measurements are made on high-resistivity specimens. Surface effects can often be observed as a difference in measured value of resistivity or Hall coefficient when the surface condition of the specimen is changed (2, 3).

5.1.6 In measuring high-resistivity samples, particular attention should be paid to possible leakage paths in other parts of the circuit such as switches, connectors, wires, cables, and the

TABLE 1 Units of Measurement

Quantity	Symbol	SI Unit	Factor [A]	Units of Measurement [B]
Resistivity	ρ	$\Omega \cdot m$	10^2	$\Omega \cdot cm$
Charge carrier concentration	n, p	m^{-3}	10^{-6}	cm^{-3}
Charge	e, q	C	1	C
Drift mobility, Hall mobility	μ, μ_H	$m^2 \cdot V^{-1} \cdot s^{-1}$	10^4	$cm^2 \cdot V^{-1} \cdot s^{-1}$
Hall coefficient	R_H	$m^3 \cdot C^{-1}$	10^6	$cm^3 \cdot C^{-1}$
Electric field	E	$V \cdot m^{-1}$	10^{-2}	$V \cdot cm^{-1}$
Magnetic flux density	B	T	10^4	gauss
Current density	J	$A \cdot m^{-2}$	10^{-4}	$A \cdot cm^{-2}$
Length	L, t, w, d a, b, c	m	10^2	cm
Potential difference	V	V	1	V

[A] The factors relate SI units to the units of measurement as in the following example:

$$1 \ \Omega \cdot m = 10^2 \ \Omega \cdot cm$$

[B] This system is not a consistent set of units. In order to obtain a consistent set, the magnetic flux density must be expressed in V · s · cm^{-2}. The proper conversion factor is:

$$1 \cdot V \cdot s \cdot cm^{-2} = 10^8 \text{ gauss}$$

like which may shunt some of the current around the sample. Since high values of lead capacitance may lengthen the time required for making measurements on high-resistivity samples, connecting cable should be as short as practicable.

5.1.7 Inhomogeneities of the carrier density, mobility, or of the magnetic flux will cause the measurements to be inaccurate. At best, the method will enable determination only of an undefined average resistivity or Hall coefficient. At worst, the measurements may be completely erroneous (2, 3, 4).

5.1.8 Thermomagnetic effects with the exception of the Ettingshausen effect can be eliminated by averaging of the measured transverse voltages as is specified in the measurement procedure (Sections 11 and 17). In general, the error due to the Ettingshausen effect is small and can be neglected, particularly if the sample is in good thermal contact with its surroundings (2, 3, 4).

5.1.9 For materials which are anisotropic, especially semiconductors with noncubic crystal structures, Hall measurements are affected by the orientation of the current and magnetic field with respect to the crystal axes (Appendix, Note X1.1). Errors can result if the magnetic field is not within the low-field limit (Appendix, Note X1.1).

5.1.10 Spurious voltages, which may occur in the measuring circuit, for example, thermal voltages, can be detected by measuring the voltage across the specimen with no current flowing or with the voltage leads shorted at the sample position. If there is a measurable voltage, the measuring circuit should be checked carefully and modified so that these effects are eliminated.

5.1.11 An erroneous Hall coefficient will be measured if the current and transverse electric field axes are not precisely perpendicular to the magnetic flux. The Hall coefficient will be at an extremum with respect to rotation if the specimen is properly positioned (see 7.4.4 or 13.4.4).

5.2 In addition to these interferences the following must be noted for van der Pauw specimens.

5.2.1 Errors may result in voltage measurements due to contacts of finite size. Some of these errors are discussed in references (1, 5, 6).

5.2.2 Errors may be introduced if the contacts are not placed on the specimen periphery (7).

5.3 In addition to the interferences described in 5.1, the following must be noted for parallelepiped and bridge-type specimens.

5.3.1 It is essential that in the case of parallelepiped or bridge-type specimens the Hall-coefficient measurements be made on side contacts far enough removed from the end contacts that shorting effects can be neglected (2, 3). The specimen geometries described in 15.3.1 and 15.3.2 are designed so that the reduction in Hall voltage due to this shorting effect is less than 1 %.

TEST METHOD A—FOR VAN DER PAUW SPECIMENS

6. Summary of Test Method

6.1 In this test method, specifications for a van der Pauw (1) test specimen and procedures for testing it are covered. A procedure is described for determining resistivity and Hall coefficient using direct current techniques. The Hall mobility is calculated from the measured values.

7. Apparatus

7.1 *For Measurement of Specimen Thickness*—Micrometer, dial gage, microscope (with small depth of field and calibrated vertical-axis adjustment), or calibrated electronic thickness gage capable of measuring the specimen thickness to ±1 %.

7.2 *Magnet*—A calibrated magnet capable of providing a magnetic flux density uniform to ±1.0 % over the area in which the test specimen is to be located. It must be possible to reverse the direction of the magnetic flux (either electrically or by rotation of the magnet) or to rotate the test specimen 180° about its axis parallel to the current flow. Apparatus, such as an auxiliary Hall probe or nuclear magnetic resonance system, should be available for measuring the flux density to an accuracy of ±1.0 % at the specimen position. If an electromagnet is used, provision must be made for monitoring the flux density during the measurements. Flux densities between 1000 and 10 000 gauss are frequently used; conditions governing the choice of flux density are discussed more fully elsewhere (2, 3, 4).

7.3 *Instrumentation:*

7.3.1 *Current Source,* capable of maintaining current through the specimen constant to ±0.5 % during the measurement. This may consist either of a power supply or a battery, in series with a resistance greater than 200 × the total specimen resistance (including contact resistance). The current source is accurate to ±0.5 % on all ranges used in the measurement. The magnitude of current required is less than that associated with an electric field of 1 V·cm^{-1} in the specimen.

7.3.2 *Electrometer or Voltmeter,* with which voltage measurements can be made to an accuracy of ±0.5 %. The current drawn by the measuring instrument during the resistivity and Hall voltage measurements shall be less than 0.1 % of the specimen current, that is, the input resistance of the electrometer (or voltmeter) must be 1000 × greater than the resistance of the specimen.

7.3.3 *Switching Facilities,* used for reversal of current flow and for connecting in turn the required pairs of potential leads to the voltage-measuring device.

7.3.3.1 *Representative Circuit,* used for accomplishing the required switching is shown in Fig. 1.

7.3.3.2 *Unity-Gain Amplifiers,* used for high-resistivity semiconductors, with input impedance greater than 1000 × the specimen resistance are located as close to the specimen as possible to minimize current leakage and circuit time-constants (8, 9). Triaxial cable is used between the specimen and the amplifiers with the guard shield driven by the respective amplifier output. This minimizes current leakage in the cabling. The current leakage through the insulation must be less than 0.1 % of the specimen current. Current leakage in the specimen holder must be prevented by utilizing a suitable high-resistivity insulator such as boron nitride or beryllium oxide.

7.3.3.3 *Representative Circuit,* used for measuring high-resistance specimens is shown in Fig. 2. Sixteen single-pole, single-throw, normally open, guarded reed relays are used to
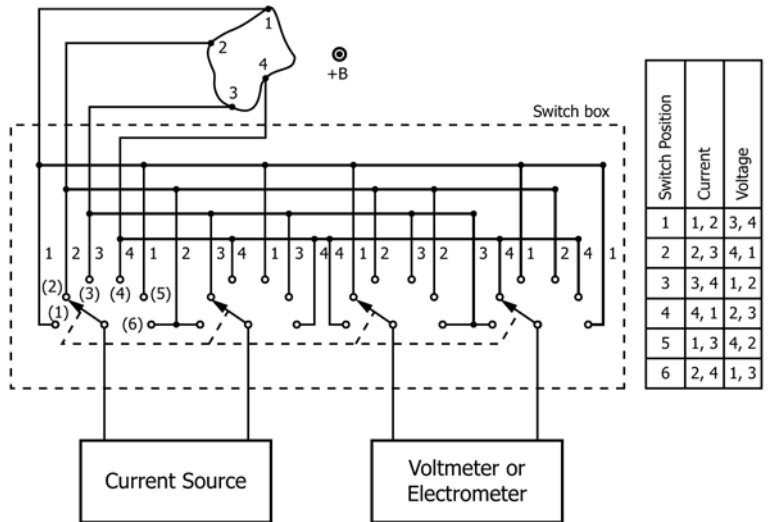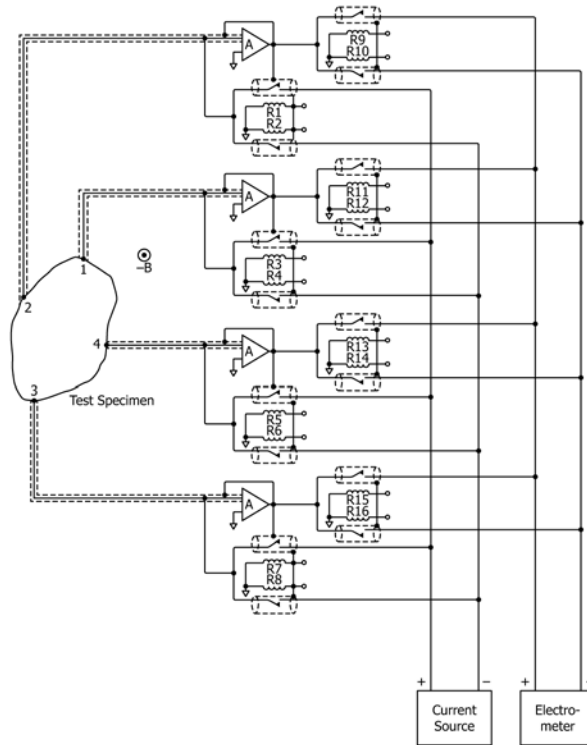
FIG. 1 Representative Manual Test Circuit for Measuring van der Pauw Specimens

NOTE 1—A—Unity gain amplifier
NOTE 2—R1–R16—Reed relays

Position	1		2		3		4		5		6	
Switches	2, 3	1, 4	1, 8	2, 7	6, 7	5, 8	4, 5	3, 6	3, 8	4, 7	1, 6	2, 5
Closed	14, 15	14, 15	12, 13	12, 13	10, 11	10, 11	9, 16	9, 16	10, 13	10, 13	11, 16	11, 16
Current	1, 2	2, 1	2, 3	3, 2	3, 4	4, 3	4, 1	1, 4	1, 3	3, 1	2, 4	4, 2
Voltage	3, 4	3, 4	4, 1	4, 1	1, 2	1, 2	2, 3	2, 3	4, 2	4, 2	1, 3	1, 3

FIG. 2 Representative Test Circuit for Measuring High-Resistivity van der Pauw Specimens

connect the current source and differential voltmeter to the appropriate specimen points. The relay closures necessary to accomplish the same switching achieved in the circuit of Fig. 1 are listed in the table of Fig. 2.

7.3.4 *Transistor Curve Tracer,* can be used for checking the linearity of contacts to low-resistivity material.

7.3.5 All instruments must be maintained within their specifications through periodic calibrations.

7.4 *Specimen Holder:*

7.4.1 *Container,* if low-temperature measurements are required, of such dimensions that it will enclose the specimen holder (7.4.3) and fit between the magnetic pole pieces. A glass or metal dewar or a foamed polystyrene boat is suitable.

7.4.2 *Temperature Detector,* located in close proximity to the test specimen and associated instruments for monitoring temperature to an accuracy of ±1°C during the measurement. This may include, for example, a thermocouple, a platinum resistance thermometer, or a suitable thermistor.

7.4.3 *Opaque Container,* used to hold the specimen in position, to maintain an isothermal region around the specimen, and to shield the specimen from light and, in the case of low-temperature measurements, from room-temperature radiation. The mounting must be arranged so that mechanical stress on the specimen does not result from differential expansion when measurements are made at temperatures different from room temperature. If liquids, such as boiling nitrogen, are used to establish low temperatures, the liquid may be allowed to enter the specimen container directly through ports that are suitably shielded against the entry of light.

7.4.4 If a metal dewar or specimen holder is used, it must be constructed of nonmagnetic materials such that the value of magnetic flux density at the specimen position will not be altered more than ±1 % by its presence.

7.4.5 To orient the specimen perpendicular to the magnetic field it is desirable to employ both geometrical and electrical tests. Sign conventions are defined in Fig. 3.

7.4.5.1 The specimen holder can usually be visually aligned parallel with the flat faces of the magnet along the long axis (usually the vertical axis) of the specimen holder in a satisfactory manner. Care should be taken that the specimen is mounted within the container so that the flat faces are parallel with an external portion of the specimen holder.

7.4.5.2 Because the dimensions are much shorter in the direction perpendicular to the long axis, electrical orientation is

preferred. This is most conveniently performed by rotating the specimen with respect to the magnetic flux and measuring the transverse voltage as a function of angle between the magnetic flux and a reference mark on the specimen holder over a range a few degrees on each side of the nominal perpendicular position. The correct position is that where the average Hall voltage is a maximum or, in some cases where orientation dependent effects are encountered, a minimum.

7.4.5.3 A more accurate method of electrical positioning involves rotation of the specimen with respect to the magnetic flux as in 7.4.5.2, but a few degrees around both positions approximately 90° away from the nominal perpendicular position. The correct angular position for the specimen during Hall-effect measurements is midway between the two points (about 180° apart) where the average transverse voltage is zero.

8. Reagents and Materials (See Section 9)

8.1 *Purity of Reagents*—All chemicals for which such specifications exist shall conform to SEMI Specifications C1. Reagents for which SEMI specifications have not been developed shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society.[6] Other grades may be used provided it is first ascertained that the reagent is sufficiently pure to permit its use without lessening the accuracy of the determination.

8.2 *Purity of Water*—When water is used it is either distilled water or deionized water having a resistivity greater than 2 MΩ·cm at 25°C as determined by the Non-Referee Tests of Test Methods D1125.

9. Test Specimen Requirements

9.1 Regardless of the specimen preparation process used, high-purity reagents and water are required.

9.2 *Crystal Perfection*—The test specimen is a single crystal.

NOTE 2—The procedure for revealing polycrystalline regions in silicon is given in Test Method F47.
NOTE 3—The crystallographic orientation of the slice may be determined if desired, using either the X-ray or optical techniques of Test Method F26.

9.3 *Specimen Shape*—The thickness shall be uniform to ±1 %. The minimum thickness is governed by the availability of apparatus which is capable of measuring the thickness to a precision of ±1 %. The test specimen shape can be formed by cleaving, machining, or photolithography. Machining techniques such as ultrasonic cutting, abrasive cutting, or sawing may be employed as required. Representative photolithographically defined test patterns are described in (10, 11, 12).

9.3.1 Although the specimen may be of arbitrary shape, one of the symmetrical configurations of Fig. 4 is recommended. The specimen must be completely free of (geometrical) holes.
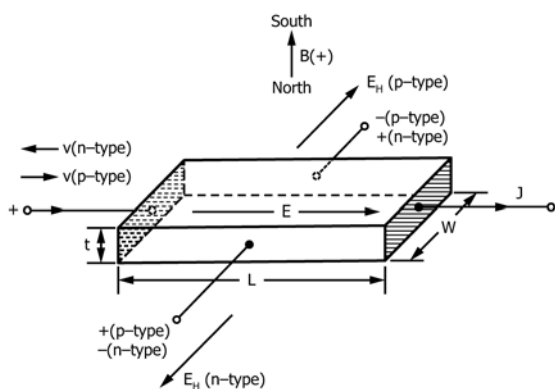
NOTE 1—The carrier velocity, V, for electrons and holes is in opposite directions as indicated.
FIG. 3 Hall-Effect Sign Conventions

(a) Circle   (b) Clover-leaf   (c) Square   (d) Rectangle
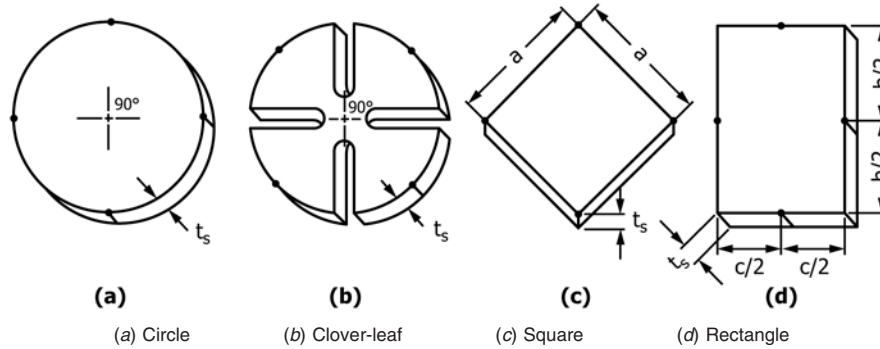
NOTE 1—Contact positions are indicated schematically by the small dots.
FIG. 4 Typical Symmetrical van der Pauw Specimens

The recommended ratio of peripheral length of the specimen, L_p, to thickness of the specimen, t, is as follows:

$$Lp \geq 15t$$

Recommended thickness is less than or equal to 0.1 cm. This specimen shape can produce erroneous results when used on anisotropic materials (see 5.1.9 and Note X1.1).

9.4 Maintain the contact dimensions as small as possible relative to the peripheral length of the specimen. If possible, place the contacts on the specimen edge. Use line or dot contacts with a maximum dimension along the peripheral length, L_p, no greater than 0.05 L_p. If the contacts must be placed on one of the two flat faces of the specimen that are separated by the dimension, t, make them as small as possible and locate them as close as possible to the edge (see 5.2.1 and 5.2.2).

10. Measurement Procedure

10.1 *Thickness Measurement*—Measure the specimen thickness (9.3) with a precision of ±1 %.

10.2 *Contact Evaluation*—Verify that all combinations of contact pairs in both polarities have linear current-voltage characteristics, without noticeable curvature, at the measurement temperature about the actual value of current to be used.

10.3 *Specimen Placement*—Place the clean and contacted specimen in its container (7.4.3). If a permanent magnet is used to provide the flux, keep the magnet and the specimen separate during the measurement of resistivity. If possible, move the magnet without disturbing the specimen and its holder, so as to minimize the possibility of a change of temperature which must remain within the ±1°C tolerance between the resistivity and Hall-effect measurements. If an electromagnet is used, be certain that the residual flux density is small enough not to affect the resistivity measurement.

10.4 *Resistivity Measurement*—Measure the temperature of the specimen. Set the current magnitude, I, to the desired value (see 5.1.2). Measure the voltages $V_{21,34}$, $V_{12,34}$, $V_{32,41}$, $V_{23,41}$, $V_{43,12}$, $V_{34,12}$, $V_{14,23}$, and $V_{41,23}$ (Note 4). Remeasure the specimen temperature to check the temperature stability. If the second measurement of the temperature differs from the first by more than 1°C, allow the temperature to stabilize further, and then repeat the procedure of 10.4.

NOTE 4—The notation to be used, $V_{AB,CD}$, refers to the potential difference $V_C − V_D$ measured between Contacts C and D when current enters Contact A and exits Contact B. Both the sign and magnitude of all voltages must be determined and recorded. For van der Pauw specimens, the contacts are labeled consecutively in counter-clockwise order around the specimen periphery. Similarly the resistance $R_{AB,CD}$ is defined as the ratio of the voltage $V_C − V_D$ divided by the current directed into Contact A and out of Contact B.

10.5 *Hall-Coefficient Measurement*—Position the specimen between the magnet-pole pieces so that the magnetic flux is perpendicular to the two flat faces of the specimen which are separated by the dimension, t, (7.4.5). If an electromagnet is used to provide the flux, follow the appropriate procedure in 10.5.1. If a permanent magnet of known flux density is used, omit the adjustment and measurement of flux density.

10.5.1 In high-mobility materials such as lightly doped *n*-type gallium arsenide, the proportionality factor, r, (see Appendix X1) varies with the applied magnetic field. For the purposes of interlaboratory comparison, users should therefore use a field of 5 gauss (0.5 mT) in the absence of other information. This effect is not expected to be significant for dopant density above 10^{17} cm$^{−3}$ in *n*-type gallium arsenide.

10.5.2 Measure the temperature of the specimen. Turn on the magnetic flux and adjust it to the desired positive value of magnetic flux density. Measure the magnetic flux density. Measure the voltages $V_{31,42}$ $(+B)$, $V_{13,42}(+B)$, $V_{42,13}(+B)$, and $V_{24,13}(+B)$ (Note 4 and Note 5). Remeasure the value of the magnetic flux density in order to check the stability of the magnet. If the second value of magnetic flux density differs from the first by more than 1 %, make the necessary changes, and repeat the procedure until the specified stability is achieved. Rotate the specimen 180° or reverse the magnetic flux, and adjust it to the same magnitude (±1 %) of magnetic flux density. Measure the voltages $V_{24,13}(−B)$, $V_{42,13}(−B)$, $V_{13,42}(−B)$, and $V_{31,42}(−B)$ (Note 4 and Note 5). Measure the temperature and magnetic flux density and check the stability as before.

NOTE 5—The parenthetical symbols $(+B)$ and $(−B)$ refer to oppositely applied magnetic fields where positive field is defined in Fig. 3.

10.6 *Cautions*—See Section 5 for discussion of spurious results.

11. Calculations

11.1 *Resistivity*—Calculate the sample resistivity from the data of 10.4. Two values of resistivity, ρ_A and ρ_B, are obtained as follows (Note 4):

$$\rho_A = \frac{1.1331 f_A t}{I} \left[V_{21,34} - V_{12,34} + V_{32,41} - V_{23,41} \right] \quad (1)$$

and

$$\rho_B = \frac{1.1331 f_B t}{I} \left[V_{43,12} - V_{34,12} + V_{14,23} - V_{41,23} \right] \Omega \cdot cm \quad (2)$$

where the constant $1.1331 \sim \pi/4 \, ln \, (2)$, the units of the voltages are in volts, the specimen thickness, t, is in centimetres, the current magnitude, I, is in amperes, and the geometrical factor f_A or f_B is a function of the resistance ratio, Q_A or Q_B, respectively:

$$Q_A = \frac{R_{21,34} - R_{12,34}}{R_{32,41} - R_{23,41}} = \frac{V_{21,34} - V_{12,34}}{V_{32,41} - V_{23,41}} \quad (3)$$

and

$$Q_A = \frac{R_{43,12} - R_{34,12}}{R_{14,23} - R_{41,23}} = \frac{V_{43;12} - V_{34,12}}{V_{14,23} - V_{41,23}} \quad (4)$$

The relationship between the factor f and Q is written explicitly and graphed in Fig. 5. If Q is less than one, take its reciprocal, and find the value of f for this number. If ρ_A is not equal to ρ_B within ±10 %, the specimen is inhomogeneous and a more uniform specimen is required. Calculate the average resistivity ρ_{av} as follows,

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \Omega \cdot cm \quad (5)$$

11.2 *Hall Coefficient*—Calculate the Hall coefficient from the data of 10.5. Two values of Hall coefficient, R_{HC} and R_{HD}, are obtained as follows (Note 4 and Note 5):

$$R_{HC} = \frac{2.50 \times 10^7 t}{BI} \left[V_{31,42} \left(+B\right) - V_{13,42} \left(+B\right) \right. \quad (6)$$
$$\left. + V_{13,42} \left(-B\right) - V_{31,42} \left(-B\right) \right]$$

and

$$R_{HD} = \frac{2.50 \times 10^7 t}{BI} \left[V_{42,13} \left(+B\right) - V_{24,13} \left(+B\right) \right. \quad (7)$$
$$\left. + V_{24,13} \left(-B\right) - V_{42,13} \left(-B\right) \right] cm^3 \cdot C^{-3}$$

If R_{HC} is not within ±10 % of R_HD, the specimen is undesirably inhomogeneous and a more uniform specimen is required. Calculate the average Hall-coefficient R_{Hav} as follows:

$$R_{Hav} = \frac{R_{HC} + R_{HD}}{2} cm^3 \cdot C^{-1} \quad (8)$$

11.3 *Hall Mobility*—Calculate the Hall mobility,

$$\mu_H \equiv \frac{|R_{Hav}|}{\rho_{av}} cm \cdot V^{-1} \cdot s^{-1} \quad (9)$$

11.4 If this procedure is to be used to obtain carrier density, users should use a value of proportionality factor, r, of 1.0 in the absence of other information (see Appendix 1.3.2).

TEST METHOD B—FOR PARALLELEPIPED OR BRIDGE-TYPE SPECIMENS

12. Summary of Test Method

12.1 In this test method, specifications for rectangular parallelepiped and bridge-type specimens and procedures for testing these structures are covered. Procedures are described for determining resistivity and Hall coefficient using direct current techniques. The Hall mobility is calculated from the measured values.
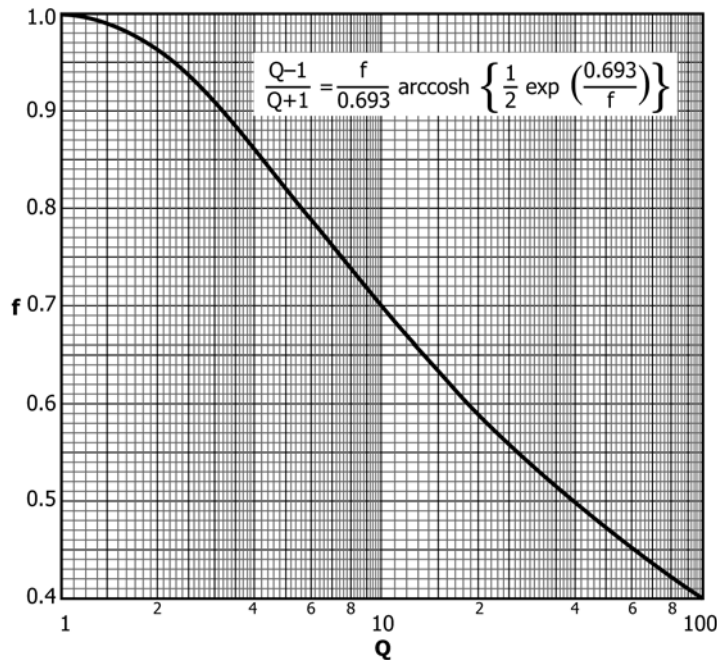

$$\frac{Q-1}{Q+1} = \frac{f}{0.693} \, arccosh \left\{ \frac{1}{2} \, exp \left(\frac{0.693}{f} \right) \right\}$$

FIG. 5 The Factor f Plotted as a Function of Q

NOTE 6—This test method for measuring resistivity is essentially equivalent to the two-probe measurement of Test Methods F43, with the exception that in the present method the potential probes may be soldered, alloyed, or otherwise attached to the semiconductor specimen.

13. Apparatus

13.1 *For Measurement of Specimen Geometry:*

13.1.1 *Micrometer, Dial Gage, Microscope (with small depth of field and calibrated vertical-axis adjustment), or Calibrated Electronic Thickness gage,* capable of measuring the specimen thickness to ±1 %.

13.1.2 *Microscope,* with crosshair and calibrated mechanical stage, capable of measuring the specimen length and width to ±1 %.

13.2 *Magnet*—A calibrated magnet capable of providing a magnetic flux density uniform to ±1.0 % over the area in which the test specimen is to be located. It must be possible to reverse the direction of the magnetic flux (either electrically or by rotation of the magnet) or to rotate the test specimen 180° about its axis parallel to the current flow. Apparatus, such as an auxiliary Hall probe or nuclear magnetic resonance system, should be available for measuring the flux density to an accuracy of ±1.0 % at the specimen position. If an electro-magnet is used, provision must be made for monitoring the flux density during the measurements. Flux densities between 1000 and 10 000 gauss are frequently used; conditions governing the choice of flux density are discussed more fully in Refs (2, 3, 4).

13.3 *Instrumentation:*

13.3.1 *Current Source,* capable of maintaining current through the specimen constant to ±0.5 % during the measurement. This may consist either of a power supply or a battery, in series with a resistance greater than 200 × the total specimen resistance (including contact resistance). The current source is accurate to ±0.5 % on all ranges used in the measurement. The magnitude of current required is less than that associated with an electric field of $1\ V{\cdot}cm^{-1}$ in the specimen.

13.3.2 An electrometer or voltmeter with which voltage measurements can be made to an accuracy of ±0.5 %. The current drawn by the measuring instrument during the resistivity and Hall voltage measurements shall be less than 0.1 % of the specimen current, that is, the input resistance of the electrometer (or voltmeter) must be 1000 × greater than the resistance of the specimen.

13.3.3 Switching facilities for reversal of current flow and for connecting in turn the required pairs of potential leads to the voltage-measuring device.

13.3.3.1 A representative circuit for accomplishing the required switching is shown in Fig. 6.

13.3.3.2 Unity-Gain Amplifiers, for high-resistivity semiconductors, with input impedance greater than 1000 × the specimen resistance are located as close to the specimen as possible to minimize current leakage and circuit time-constants (8, 9). Triaxial Cable, used between the specimen and the amplifiers with the guard shield driven by the respective amplifier output. This minimizes current leakage in the cabling. The current leakage through the insulation must be less than 0.1 % of the specimen current. Current leakage in the specimen holder must be prevented by utilizing a suitable high-resistivity insulator such as boron nitride or beryllium oxide.

13.3.4 *Transistor Curve Tracer,* can be used for checking the linearity of contacts to low-resistivity material.

13.3.5 All instruments must be maintained within their specifications through periodic calibrations.

13.4 *Specimen Holder:*

13.4.1 A container of such dimensions that it will enclose the specimen holder (13.4.3) and fit between the magnetic pole pieces. A glass or metal dewar or a foamed polystyrene boat is suitable.

13.4.2 A temperature detector located in close proximity to the test specimen and associated instruments for monitoring temperature to an accuracy of ±1°C during the measurement.
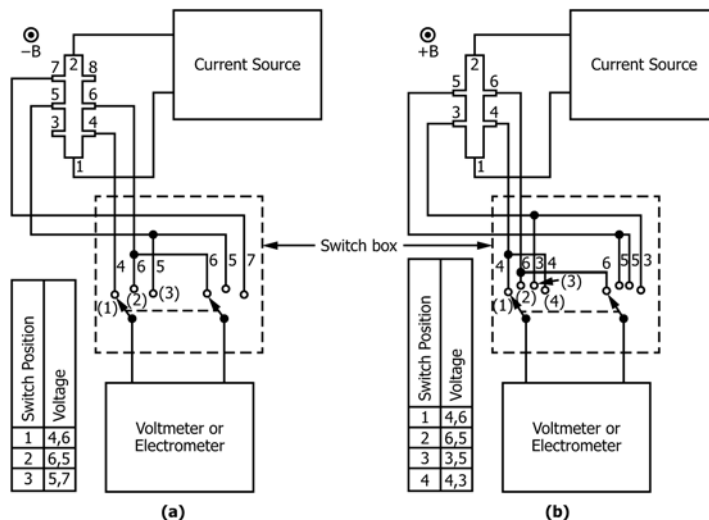
NOTE 1—(a) Eight-contact specimen   (b) Six-contact specimen

FIG. 6 Representative Test Circuits for Measuring Bridge-Type and Parallelepiped Specimens

This may include, for example, a thermocouple, a platinum resistance thermometer, or a suitable thermistor.

13.4.3 An opaque container to hold the specimen in position, to maintain an isothermal region around the specimen, and to shield the specimen from light and, in the case of low-temperature measurements, from room-temperature radiation. The mounting must be arranged so that mechanical stress on the specimen does not result from differential expansion when measurements are made at temperatures different from room temperature. If liquids, such as boiling nitrogen, are used to establish low temperatures, the liquid may be allowed to enter the specimen container directly through ports that are suitably shielded against the entry of light.

13.4.4 If a metal dewar or specimen holder is used, it must be constructed of nonmagnetic materials such that the value of magnetic flux density at the specimen position will not be altered more than $\pm 1\%$ by its presence.

13.4.5 To orient the specimen perpendicular to the magnetic field it is desirable to employ both geometrical and electrical tests. Sign conventions are defined in Fig. 3.

13.4.5.1 The specimen holder can usually be visually aligned parallel with the flat faces of the magnet along the long axis (usually the vertical axis) of the specimen holder in a satisfactory manner. Care should be taken that the specimen is mounted within the container so that the flat faces are parallel with an external portion of the specimen holder.

13.4.5.2 Because the dimensions are much shorter in the direction perpendicular to the long axis, electrical orientation is preferred. This is most conveniently performed by rotating the specimen with respect to the magnetic flux and measuring the transverse voltage as a function of angle between the magnetic flux and a reference mark on the specimen holder over a range a few degrees on each side of the nominal perpendicular position. The correct position is that where the average Hall voltage is a maximum or, in some cases where orientation dependent effects are encountered, a minimum.

13.4.5.3 A more accurate method of electrical positioning involves rotation of the specimen with respect to the magnetic flux as in 13.4.5.2, but a few degrees around both positions approximately 90° away from the nominal perpendicular position. The correct angular position for the specimen during Hall-effect measurements is midway between the two points (about 180° apart) where the average transverse voltage is zero.

14. Reagents and Materials (See Section 15)

14.1 *Purity of Reagents*—All chemicals for which such specifications exist shall conform to SEMI Specifications C1. Reagents for which SEMI specifications have not been developed shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society.[6] Other grades may be used provided it is first ascertained that the reagent is sufficiently pure to permit its use without lessening the accuracy of the determination.

14.1.1 *Purity of Water*—When water is used it is either distilled water or deionized water having a resistivity greater than 2 MΩ·cm at 25°C as determined by the Non-Referee Tests of Test Method D1125.

15. Test Specimen Requirements

15.1 Regardless of the specimen preparation process used, high-purity reagents and water are required.

15.2 *Crystal Perfection*—The test specimen is a single crystal.

NOTE 7—The procedure for revealing polycrystalline regions in silicon is given in Test Method F47.

NOTE 8—The crystallographic orientation of the slice may be determined if desired, using either the X-ray or optical techniques of Test Method F26.

15.3 *Specimen Shape*—The thickness shall be uniform to $\pm 1\%$ and shall not exceed 0.10 cm. The minimum thickness is governed by the availability of apparatus which is capable of measuring the thickness to a precision of $\pm 1\%$. Machine or cleave the test specimen into one of the forms shown in Fig. 7 and Fig. 8, respectively. Machining techniques such as ultrasonic cutting, abrasive cutting, or sawing are employed as required.

15.3.1 *Parallelepiped Specimen*—The total length of the specimen shall be between 1.0 and 1.5 cm. The sides must be perpendicular to the specimen surface to within $\pm 0.5°$. If possible, the length to width ratio should be greater than 5, but in no case shall it be less than 4. The sample configuration is shown in Fig. 7(*a*).

15.3.2 *Bridge-Type Specimen*—Contact positions on this type of specimen are determined by the configuration of the die used in cutting it. The dies must enable sample dimensions to be held to a tolerance of 1 %. Any of the contact configurations shown in Fig. 8 are recommended. In some configurations the protruding side arms of the specimen are enlarged in cross section to facilitate the application of contacts. The ends of the specimen may also be enlarged in order to allow the use of contacts applied to the top surface, as in the case of evaporated contacts. See Fig. 8(*c*) and Fig. 8(*d*). The enlarged portions of the ends shall not be included in the total specimen length specified above.
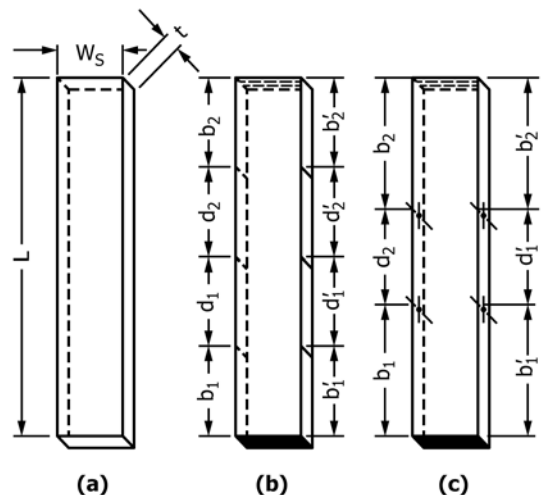
NOTE 1—Current contacts cover the entire end of the specimen. Potential contacts may be either lines as in (*b*) or dots as in (*c*).
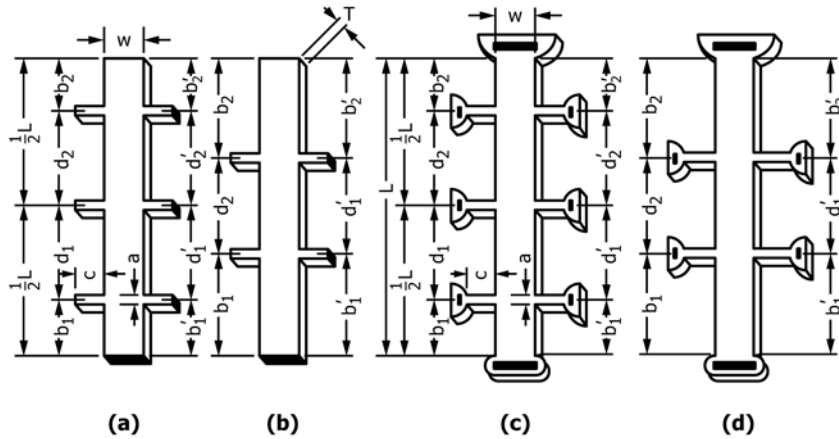FIG. 7 Typical Parallelepiped Specimens

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FIG. 8 Typical Bridge-Type Specimens

15.3.3 *Eight-Contact Specimen*—The geometry of the specimen is defined below, see Fig. 8(*a*) and 8(*c*):

$$L \geq 4w$$
$$w \geq 3a$$
$$b_1, b_2 \geq w$$
$$t \leq 0.1 \text{ cm}$$
$$c \geq 0.1 \text{ cm}$$
$$1.0 \text{ cm} \leq L \leq 1.5 \text{ cm}$$
$$b_1 = b_1' \pm 0.005 \text{ cm}$$
$$b_2 = b_2' \pm 0.005 \text{ cm}$$
$$d_1 = d_1' \pm 0.005 \text{ cm}$$
$$d_2 = d_2' \pm 0.005 \text{ cm}$$
$$b_1 + d_1 = (1/2)L + 0.005 \text{ cm}$$
$$b_1' = d_1' = (1/2)L \pm 0.005 \text{ cm}$$
$$b_1 \approx b_2, \qquad d_1 \approx d_2$$

15.3.4 *Six-Contact Specimen*—The geometry of the specimen is defined as follows, see Fig. 8(b) and 8(d):

$$L \geq 5w$$
$$w \geq 3a$$
$$b_1, b_2 \geq 2w$$
$$t \leq 0.1 \text{ cm}$$
$$c \geq 0.1 \text{ cm}$$
$$1.0 \text{ cm} \leq L \leq 1.5 \text{ cm}$$
$$b_1 = b_1' \pm 0.005 \text{ cm}$$
$$b_2 = b_2' \pm 0.005 \text{ cm}$$
$$d_2 = d_1' \pm 0.005 \text{ cm}$$
$$b_1 \approx b_2$$

15.4 *Contact Requirements:*

15.4.1 *Parallelepiped Specimens*—The two ends of the specimen must be completely covered with current contacts. Make the contact interface with the specimen for the other (voltage measurement) contacts less than 0.02 cm in width. If six potential contacts are employed, position them as shown in Fig. 7(*b*). If four voltage contacts are employed, position them as shown in Fig. 7(*c*).

15.4.2 *Bridge-Type Specimens Without Expanded End Contacts*—Completely cover the ends of the specimen with current contacts.

15.4.3 *Bridge-Type Specimens with Expanded Side and End Contacts*—Place the contacts on appropriate locations on one

of the two flat faces of the specimen which are separated by the dimension, *t* (see the shaded areas in Fig. 8(*c*) and (*d*)).

16. Measurement Procedure

16.1 *Dimension Measurement*—The specimen length, width, and thickness must be measured with a precision of ±1 % (13.1).

16.2 *Contact Evaluation*—Verify that all combinations of contact pairs in both polarities have linear current-voltage characteristics, without noticeable curvature, at the measurement temperature about the actual value of current to be used.

16.3 *Specimen Placement*—Place the clean and contacted specimen in its container (13.4.3). If a permanent magnet is used to provide the flux, keep the magnet and the specimen separate during the measurement of resistivity. If possible, move the magnet without disturbing the specimen and its holder, so as to minimize the possibility of a change of temperature which must remain within the ±1°C tolerance between the resistivity and Hall-effect measurements. If an electromagnet is used, be certain that the residual flux density is small enough not to affect the resistivity measurement.

16.4 *Resistivity Measurement:*

16.4.1 *Eight-Contact Specimen*—Measure the specimen temperature. With no magnetic flux, measure the voltages $V_{12,46}$ and $V_{12,57}$ (Note 9). Reverse the current and measure $V_{21,46}$ and $V_{21,57}$. Remeasure the specimen temperature to check the temperature stability. If the second temperature measurement differs from the first by more than 1°C, allow the temperature to stabilize further, and then repeat the procedure of 16.4.1.

NOTE 9—The notation to be used, $V_{AB,CD}$, refers to the potential difference $V_C - V_D$ measured between Contact C and D when current enters Contact A and exits Contact B. Both the sign and magnitude of all voltages must be determined and recorded. For parallelepiped and bridge-type specimens the contacts are labeled in Fig. 6. Similarly the resistance $R_{AB,CD}$ is defined as the ratio of the voltage $V_C - V_D$ divided by the current directed into Contact *A* and out of Contact *B*.

16.4.2 *Six-Contact Specimen*—Measure the specimen temperature. With no magnetic flux, measure the voltages $V_{12,46}$

and $V_{12,35}$ (Note 9). Reverse the current and measure $V_{21,46}$ and $V_{21,35}$. Remeasure the specimen temperature to check the temperature stability. If the second temperature measurement differs from the first by more than 1°C, allow the temperature to stabilize further, and then repeat the procedure of 16.4.2.

16.5 *Hall-Coefficient Measurement:*

16.5.1 *Eight-Contact Specimen*—Measure the specimen temperature. Turn on the magnetic flux, and adjust it to the desired positive value of magnetic flux density. Measure the magnetic flux density. Measure the voltage $V_{12,65}(+B)$. Reverse the current and measure $V_{21,65}(+B)$ (Note 5 and Note 9). Remeasure the magnetic flux density to check the stability of the magnet. If the second value of magnetic flux density differs from the first by more than 1 %, make the necessary changes and repeat the procedure until the specified stability is achieved. Rotate the specimen 180° or reverse the magnetic flux and adjust it to the same magnitude (±1 %) of magnetic flux density. Measure the magnetic flux density. Repeat the voltage measurements to obtain $V_{21,65}(-B)$. Reverse the current and repeat the measurements to obtain $V_{12,65}(-B)$. Verify the stability of the magnetic flux density and temperature as before.

NOTE 10—The parenthetical symbols (+B) and (−B) refer to oppositely applied magnetic fields where positive field is defined in Fig. 2.

16.5.2 *Six-Contact Specimen*—Measure the specimen temperature. Turn on the magnetic flux, and adjust it to the desired positive value of magnetic flux density. Measure the magnetic flux density. Measure the voltages $V12,65(+B)$ and $V_{12,43}(+B)$ (Note 5 and Note 9). Reverse the current and measure $V_{21,65}(+B)$ and $V_{21,43}(+B)$. Remeasure the magnetic flux density to check the stability of the magnetic field. If the second value of magnetic flux density differs from the first by more than 1 %, make the necessary changes and repeat the procedure until the specified stability is achieved. Rotate the specimen 180° or reverse the magnetic field and adjust it to the same magnitude (±1 %) of magnetic flux density. Measure the magnetic flux density. Repeat the voltage measurements to obtain $V_{21,65}(-B)$ and $V_{21,43}(-B)$. Reverse the current and repeat the measurements to obtain $V_{12,65}(-B)$ and $V_{12,43}(-B)$. Verify the stability of the magnetic field and temperature as before.

16.6 *Cautions*—See Section 5 for a discussion of spurious results.

17. Calculations

17.1 *Resistivity:*

17.1.1 *Eight-Contact Specimens*—Calculate the sample resistivity at the two positions on the specimens from the data of 16.4.1. The resistivity at one position (ρ_A) is given by (Note 9):

$$\rho_A = \frac{V_{12,46} - V_{21,46}}{2I} \frac{Wt}{d_1{}'} \, \Omega \cdot cm \tag{10}$$

and the resistivity at the other position (ρ_B) is given by:

$$\rho_B = \frac{V_{12,57} - V_{21,57}}{2I} \frac{wt}{d_2} \, \Omega \cdot cm \tag{11}$$

where the units of the voltages are in volts, current is in amperes and w, t, $d_1{}'$, and d_2 are in centimetres.

17.1.2 *Six-Contact Specimens*—Computed from the data of 16.4.2 with ρ_A given by the equation of 17.1.1 and ρ_B given by (Note 9),

$$\rho_B = \frac{V_{12,35} - V_{21,35}}{2I} \frac{wt}{d_2} \, \Omega \cdot cm \tag{12}$$

17.1.3 If ρ_A and ρ_B are not equal within ±10 %, the specimen is undesirably inhomogeneous and a more uniform specimen is required. Calculate the average resistivity ρ_{av},

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \, \Omega \cdot cm \tag{13}$$

17.2 *Hall Coefficient:*

17.2.1 *Eight-Contact Specimen*—Calculate the Hall coefficient from the data of 16.5.1 (Note 5 and Note 9),

$$R_{HA} = 2.50 \times 10^{7} \frac{t}{B} \tag{14}$$

$$\cdot \frac{V_{12,65}(+B) - V_{21,65}(+B) + V_{21,65}(-B) - V_{21,65}(-B)}{I} \, cm^3 \cdot C^{-1}$$

where the units of the voltage are in volts, current is in amperes, t is in centimetres, and B is in gauss. R_{HA} will be negative for *n*-type material and positive for *p*-type material.

17.2.2 *Six-Contact Specimen*—Using the data of 16.5.2 calculate R_{HA} as in 17.2.1 and a second Hall coefficient R_{HB} as follows (Note 5 and Note 9),

$$R_{HB} = 2.50 \times 10^{7} \frac{t}{B} \tag{15}$$

$$\cdot \frac{V_{12,43}(+B) - V_{21,43}(+B) + V_{21,43}(-B) - V_{12,43}(-B)}{I} \, cm^3 \cdot C^{-1}$$

If R_{HA} and R_{HB} are not equal within ±10 %, the specimen is undesirably inhomogeneous and a more uniform specimen is required. When two values of Hall coefficient are available calculate the average Hall coefficient R_{Hav} as follows,

$$R_{Hav} = \frac{R_{HA} + R_{HB}}{2} \, cm^3 \cdot C^{-1} \tag{16}$$

17.3 *Hall Mobility*—Calculate the Hall mobility with R_{Hav} given by R_{HA} for the case of an eight-contact specimen.

$$\mu_H \equiv \frac{|R_{Hav}|}{\rho_{av}} \, cm^2 \cdot v^{-1} \cdot s^{-1} \tag{17}$$

18. Report

18.1 For referee tests report the following information:

18.1.1 Identification of test specimen,

18.1.2 Test temperature,

18.1.3 Specimen shape used, orientation, and corresponding dimensions,

18.1.4 Magnitude and polarity of all voltages and magnetic-flux density, and

18.1.5 Calculated average resistivity, average Hall-coefficient (including sign), and Hall mobility.

19. Precision and Bias[7]

19.1 An interlaboratory test program was conducted in 2004 to obtain between-laboratory variability for sheet resistance

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[7] A research report containing detailed information is on file at ASTM International Headquarters. Request RR:F01-1018.

and mobility. Four wafers, two thin and two thick, were cleaved into a set of sites. Four sites from each wafer were sent to 11 laboratories and each site was tested by 10 or 11 laboratories. Only one measurement was conducted on each wafer so repeatability cannot be determined.

19.2 Tables 2-4 are summaries of the typical average and reproducibility standard deviation found for sheet resistance, mobility and density for each wafer. The sites did vary in average level and reproducibilty standard deviation, but were within expected variation to permit pooling of the results.

19.3 Laboratories had statistically significant systematic differences for mobility and density which is reflected in the reproducibility standard deviation. These differences, however, may not be of practical significance.

19.4 *Within Laboratory Intermediate Precision or Uncertainty*—A single laboratory provided readings on each position on 6 to 8 time periods over a 10-month period. This can be evaluated as measure of within laboratory intermediate precision or uncertainty. In accordance with Practice E2554 an estimate of standard deviation has been computed. In all cases these results were much smaller than reproducibilty standard deviation. These are probably larger than would be expected for repeatability (very short time between readings) but are illustrative of what long-term variation within a given laboratory might experience.

20. Keywords

20.1 gallium arsenide; Hall coefficient; Hall data; Hall mobility; Hall resistivity; semiconductor; silicon; single crystal; van der Pauw

TABLE 2 Sheet Resistance

Wafer	Avg of 4 Sites	$S_R{}^A$	R^B
P2-Thick	226.12	2.24	6.28
S2-Thick	163.98	1.13	3.16
P1-Thin	557.60	17.89	50.09
S1-Thin	1138.42	56.59	158.44

$^A S_R$ is a pooled estimate of reproducibility standard based on 4 sites.
$^B R$ is the largest difference one might expect for single readings taken at two laboratories (95 % of the time).

TABLE 3 Mobility

Wafer	Avg of 4 Sites	$S_R{}^A$	R^B
S2-Thick	2767.2	78.4	219.5
P2-Thick	3070.2	85.2	238.6
S1-Thin	4057.8	105.9	296.4
P1-Thin	4570.7	115.6	323.6

$^A S_R$ is a pooled estimate of reproducibility standard based on 4 sites.
$^B R$ is the largest difference one might expect for single readings taken at two laboratories (95 % of the time).

TABLE 4 Density (x 1.0E+12)

Wafer	Avg of 4 Sites	$S_R{}^A$	R^B
S2-Thick	9.950	0.178	0.499
P2-Thick	12.405	0.239	0.669
S1-Thin	2.501	0.104	0.292
P1-Thin	1.368	0.062	0.173

$^A S_R$ is a pooled estimate of reproducibility standard based on 4 sites.
$^B R$ is the largest difference one might expect for single readings taken at two laboratories (95 % of the time).

TABLE 5 Sheet Resistance (single laboratory uncertainty sd)

Wafer	Avg of 4 Sites	sd Uncertainty
S2-Thick	226.88	1.38
P2-Thick	164.33	1.06
P1-Thin	556.57	7.25
S1-Thin	1126.41	51.63

TABLE 6 Mobility

Wafer	Avg of 4 Sites	sd Uncertainty
S2-Thick	2774.3	27.4
P2-Thick	3088.4	32.1
P1-Thin	4644.9	58.0
S1-Thin	4146.2	92.2

TABLE 7 Density (x 1.0E+12)

Wafer	Avg of 4 Sites	sd Uncertainty
S2-Thick	9.951	0.093
P2-Thick	12.383	0.090
P1-Thin	2.475	0.024
S1-Thin	1.358	0.040

APPENDIX

(Nonmandatory Information)

X1. INTERPRETATION

X1.1 The interpretation of the results of these measurements in terms of semiconductor material parameters is often not straightforward. When more information is needed than is provided here, the reader is referred to the literature (**2, 3, 4**).

X1.2 The *resistivity* of a material is the ratio of the potential gradient parallel to the current in the material to the current density. For the purposes of this method, the resistivity shall always be determined for the case of zero magnetic flux.

X1.2.1 In extrinsic semiconductors with a single type of charge carrier the resistivity is related to the fundamental material properties as follows:

$$\rho = \frac{1}{e\mu n} \qquad (X1.1)$$

where:

ρ = resistivity,
e = magnitude of the electronic charge,
μ = magnitude of the mobility of the charge carrier (X1.5), and
n = charge carrier density.

When both electrons and holes are present, the following equation applies:

$$\rho = \frac{1}{e(\mu_n n + \mu_p p)} \qquad (X1.2)$$

where n and p represent the electron and hole densities, respectively, and μ_n and μ_p represent the corresponding average electron and hole mobilities. Eq 2 is appropriate for intrinsic semiconductors (where the electron and hole concentrations are approximately equal).

X1.3 When mutually perpendicular electric and magnetic fields are impressed on an isotropic solid, the charge carriers are deflected in the third mutually perpendicular direction. If the current in this direction is constrained by the boundary of the solid (to be zero), a *transverse voltage* is developed to oppose the deflection of the charge carriers. The magnetic-field dependence of the transverse voltage has both an odd and an even component. The even component of transverse voltage is attributed to magnetoresistance and contact misalignment voltages. The odd component is by definition the *Hall voltage*, that is, the component of the transverse voltage which reverses sign with reversal of magnetic-field direction.

X1.4 The *Hall coefficient* is the ratio of the Hall electric field (due to the Hall voltage) to the product of the current density and the magnetic flux density (see Fig. 3) as follows:

$$R_H = \frac{E_H}{JB} \qquad (X1.3)$$

where:

R_H = Hall coefficient,
E_H = Hall electric field,
J = current density, and
B = magnetic flux density.

NOTE X1.1—The Hall coefficient is independent of crystal orientation provided the crystal structure is cubic and the measurements are performed at low-magnetic fields. For noncubic crystals, the orientation of the current and magnetic field directions must be chosen appropriately. The low-magnetic-field condition is given as follows:

$$(\mu B)^2 \ll 1$$

where the mobility, μ, is given in m^2/V·s and the magnetic flux density, B, is given in tesla. As an example, high-mobility n-type gallium arsenic with a mobility of 4000 cm^2/V·s measured in a field of 0.5 T (5 kgauss) gives a value $(\mu B)^2 = 0.04$ which should be low enough so as not to introduce significant field-dependent anisotropies into R_H.

X1.4.1 For *n*-type extrinsic semiconductors, in which the conduction is primarily by electrons, the Hall coefficient is negative; for *p*-type extrinsic semiconductors, in which the conduction is primarily by holes, it is positive. Conventions relating the signs of the various quantities are shown in Fig. 3.

X1.4.2 For extrinsic semiconductors at temperatures below the intrinsic region with conduction dominated by a single charge-carrier type, the Hall coefficient is related to the material properties as follows:

$$R_H = \frac{r}{nq} \qquad (X1.4)$$

where:

r = proportionality factor and
q = charge of the carrier ($-e$ for electrons and $+e$ for holes).

The proportionality factor, which is of the order of unity, depends on the details of the band structure, scattering mechanism or mechanisms, specimen temperature, magnetic-flux density, and (in some cases) specimen orientation (**13**). Detailed knowledge of r is required in order to determine accurately the charge-carrier density from the Hall coefficient

measured in a specific instance. In many cases, such information is not known and *r* must be estimated. A summary of the available information is given separately (**2, 3, 4, 14**) . When both electrons and holes are present in comparable quantities, the density of each type cannot be found from a single, low-field Hall-coefficient measurement, because the Hall-coefficient depends on the density and mobility of each carrier (**2, 3, 4**).

X1.4.3 In principle, the proportionality factor r can experimentally be made equal to unity by performing measurements in the "high-field region" where the product of the magnetic field and the mobility is much greater than one:

$$\mu B \gg 1$$

Unfortunately, this condition is only practical in special cases (**15**) due to the high-magnetic field required for most semiconductors at room temperature.

X1.5 The average *Hall mobility* is the ratio of the magnitude of the Hall coefficient to the resistivity; it is readily interpreted only in a system with carriers of one charge type.

X1.6 The *drift mobility* of a charge carrier is the ratio of the mean velocity of the carriers to the applied electric field. In a single carrier system, either *n*- or *p*-type, the drift mobility, μ is related to the average Hall mobility, μ_H by the proportionality factor *r*,

$$\mu_H = r\mu \qquad (X1.5)$$

If *r* is known for the material being studied and the conditions of the measurement (**2, 3, 4**), it is possible to obtain an accurate value of drift mobility from measurements of the Hall coefficient and resistivity.

REFERENCES

(**1**) van der Pauw, L. J.,"A Method of Measuring Specific Resistivity and Hall Effect of Discs of Arbitrary Shape," *Philips Research Reports*, Vol 13, 1958, pp. 1–9.

(**2**) Putley, E. H.,*Hall Effect and Related Phenomena*, Butterworth & Co., Ltd., London, 1960.

(**3**) Beer, A. C., *Galvanomagnetic Effects in Semiconductors*, Academic Press, Inc., New York, NY, 1963.

(**4**) Stillman, G. E., Wolfe, C. M., and Dimmock, J. O.,"Hall Coefficient Factor for Polar Mode Scattering in *n*-type GaAs," *Journal of Physics and Chemistry of Solids*, Vol 31, 1970, pp. 1119–1204.

(**5**) Chwang, R., Smith, B. J., and Crowell, C. R.,"Contact Size Effects on the van der Pauw Method for Resistivity and Hall Coefficient Measurement," *Solid-State Electronics*, Vol 17, 1974, pp. 1217–1227.

(**6**) Versnel, W., "Analysis of the Greek Cross, a van der Pauw Structure with Finite Contacts," *Solid-State Electronics*, Vol 22, 1979, pp. 911–914.

(**7**) Buehler, M. G., and Thurber, W. R., "Measurements of the Resistivity of a Thin Sample with a Square Four-Probe Array," *Solid-State Electronics*, Vol 20, 1977, pp. 403–406.

(**8**) Hemenger, P. M.,"Measurements of High Resistivity Semiconductors Using the van der Pauw Method," *Review Science Instruments*, Vol 44, 1973, pp. 698–700.

(**9**) Look, D. C., and Farmer, J. W., "Automated, High Resistivity Hall Effect and Photoelectronic Apparatus," *Journal Physics E: Science Instruments*, Vol 14, 1981, pp. 472–477.

(**10**) Johansson, N. G. E., Mayer, J. W., and Marsh, O. J.," Technique Used in Hall Effect Analysis of Ion Implanted Si and Ge," *Solid-State Electronics*, Vol 13, 1970, pp. 317–335.

(**11**) Crossley, P. A., and Ham, W. E., "Use of Test Structures and Results of Electrical Tests for Silicon-on-Sapphire Integrated Circuit Processes," *Journal of Electronic Materials*, Vol 2, 1973, pp. 465–483.

(**12**) Buehler, M. G.,"Semiconductor Measurement Technology: Microelectronic Test Pattertn NBS-3 for Evaluating the Resistivity-Dopant Density Relationship of Silicon," *NBS Special Publication*400-22, May 1976.

(**13**) Allgaier, R. S.,"Some General Input-Output Rules Governing Hall Coefficient Behavior," *The Hall Effect and Its Applications*, ed. by C. L. Chien and C. R. Westgate, Plenum Press, New York, NY, 1980.

(**14**) Szmulowicz, F.,"Calculation of Optical- and Acoustic-Phonon-Limited Conductivity and Hall Mobilities for p-Type Silicon and Germanium," *Physical Review B*, Vol 28, 1983, pp. 5943–5963.

(**15**) Mitchel, W. C., and Hemenger, P. M., "Temperature Dependence of the Hall Factor and the Conductivity Mobility in p-Type Silicon," *Journal of Applied Physics*, Vol 53, 1982, pp. 6880–6884.