Designation: F76 – 08 (Reapproved 2016)\textsuperscript{c1}

**Standard Test Methods for Measuring Resistivity and Hall Coefficient and Determining Hall Mobility in Single-Crystal Semiconductors\textsuperscript{1}**

This standard is issued under the fixed designation F76; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reaffirmation. A superscript epsilon (\(\epsilon\)) indicates an editorial change since the last revision or reaffirmation.

\[\epsilon^1\text{ NOTE}——\text{In 10.5.1, second sentence, (0.5 T) was corrected editorially to (0.5 mT) in May 2017.}\]

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**\textsuperscript{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, Bridge** 3—This test method requires a specimen of specified shape. Contact requirements are specified for both the parallelepiped and bridge 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:\textsuperscript{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 Semiconducting Single Crystal (Withdrawn 2003)\textsuperscript{4}
- F43 Test Methods for Resistivity of Semiconductor Materials (Withdrawn 2003)\textsuperscript{4}

\[\text{For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard’s Document Summary page on the ASTM website.}\]

\[\text{The last approved version of this historical standard is referenced on www.astm.org.}\]
F47 Test Method for Crystallographic Perfection of Silicon by Preferential Etch Techniques
F418 Practice for Preparation of Samples of the Constant Composition Region of Epitaxial Gallium Arsenide Phosphide for Hall Effect Measurements (Withdrawn 2008)

2.2 SEMI Standard:
C1 Specifications for Reagents

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:

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

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 such as switches, connectors, wires, cables, and the

### Table 1 Units of Measurement

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>SI Unit</th>
<th>Factor</th>
<th>Units of Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity</td>
<td>( \rho )</td>
<td>( \Omega \cdot \text{m} )</td>
<td>( 10^2 )</td>
<td>( \Omega \cdot \text{cm} )</td>
</tr>
<tr>
<td>Charge carrier concentration</td>
<td>( n, p )</td>
<td>( m^3 )</td>
<td>( 10^{-6} )</td>
<td>( \text{cm}^{-3} )</td>
</tr>
<tr>
<td>Charge</td>
<td>( e, q )</td>
<td>C</td>
<td>1</td>
<td>C</td>
</tr>
<tr>
<td>Drift mobility, Hall mobility</td>
<td>( \mu_B )</td>
<td>( m^3 \cdot V^{-1} \cdot s^{-1} )</td>
<td>( 10^4 )</td>
<td>( \text{cm}^3 \cdot V^{-1} \cdot s^{-1} )</td>
</tr>
<tr>
<td>Hall coefficient</td>
<td>( B_{</td>
<td></td>
<td>} )</td>
<td>( \text{V} \cdot \text{m}^{-1} )</td>
</tr>
<tr>
<td>Electric field</td>
<td>( E )</td>
<td>( \text{V} \cdot \text{m}^{-1} )</td>
<td>( 10^4 )</td>
<td>( \text{gauss} )</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>( B )</td>
<td>T</td>
<td>1</td>
<td>T</td>
</tr>
<tr>
<td>Current density</td>
<td>( J )</td>
<td>A·m⁻²</td>
<td>( 10^{-4} )</td>
<td>A·cm⁻²</td>
</tr>
<tr>
<td>Length</td>
<td>( L, l, w, d )</td>
<td>m</td>
<td>( 10^2 )</td>
<td>cm</td>
</tr>
<tr>
<td>Potential difference</td>
<td>( V )</td>
<td>V</td>
<td>1</td>
<td>V</td>
</tr>
</tbody>
</table>

*The factors relate SI units to the units of measurement as in the following example:

\[ 1 \Omega \cdot \text{m} = 10^2 \Omega \cdot \text{cm} \]

*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:

\[ 1 \cdot \text{V} \cdot \text{s} \cdot \text{cm}^{-2} = 10^8 \text{ gauss} \]
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 to determine if there are introduced errors (2, 3, 4).

5.1.11 An erroneous Hall voltage may be measured if the current and transverse electric field are 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 measurements. This may consist either of a power supply or a battery, in series with a resistance greater than 200 × the total specimen resistance. This may consist either of a power supply or a battery, in series with a resistance greater than 200 × the total specimen resistance (2, 3). The current source is shown in Fig. 1.

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-resistivity specimens is shown in Fig. 2. Sixteen single-pole, single-throw, normally open, guarded reed relays are used to...