Designation: F 374 – 02

Standard Test Method for Sheet Resistance of Silicon Epitaxial, Diffused, Polysilicon, and Ion-implanted Layers Using an In-Line Four-Point Probe with the Single-Configuration Procedure[1]

This standard is issued under the fixed designation F 374; 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 reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the direct measurement of the average sheet resistance of thin layers of silicon with diameters greater than 15.9 mm (0.625 in.) which are formed by epitaxy, diffusion, or implantation onto or below the surface of a circular silicon wafer having the opposite conductivity type from the thin layer to be measured or by the deposition of polysilicon over an insulating layer. Measurements are made at the center of the wafer using a single-configuration of the four-probe, that is, with the current being passed through the outer pins and the resulting potential difference being measured with the inner pins.

1.2 This test method is known to be applicable on films having thickness at least 0.2 µm. It can be used to measure sheet resistance in the range 10 to 5000 Ω, inclusive.

1.2.1 The principle of the test method can be extended to cover lower or higher values of sheet resistance; however, the precision of the method has not been evaluated for sheet resistance ranges other than those given in 1.2.

NOTE 1—The minimum value of the diameter is related to tolerances on the accuracy of the measurement through the geometric correction factor. The minimum layer thickness is related to danger of penetration of the probe tips through the layer during measurement.

1.3 Procedures for preparing the specimen, for measuring its size, and for determining the temperature of the specimen during the measurement are also given. Abbreviated tables of correction factors appropriate to circular geometry are included with the method so that appropriate calculations can be made conveniently.

NOTE 2—The principles of this test method are also applicable to other semiconductor materials, but neither the appropriate conditions nor the expected precision have been determined. Other geometries can also be measured, but only comparative measurements using similar geometrical conditions should be used unless proper geometrical correction factors are known.

NOTE 3—Some relaxations of test conditions are mentioned in order to assist in applying the principles of the method to nonreferee applications, for which a complete nonreferee method has not yet been developed. The relaxed test conditions given are consensus conditions only and their effect on measurement precision and accuracy has not been explored.

1.4 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.5 *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.* Specific hazard statements are given in Section 9.

2. Referenced Documents

2.1 *ASTM Standards:*

D 5127 Guide for Ultra Pure Water Used in the Electronics and Semiconductor Industry[2]

E 1 Specification for ASTM Thermometers[3]

F 42 Test Method for Conductivity Type of Extrinsic Semiconducting Materials[4]

F 1529 Test Method for Sheet Resistance Uniformity Evaluation by In-Line Four-Point Probe with the Dual-Configuration Procedure[4]

2.2 *SEMI Standards:*

C3.15 Standard for Nitrogen (N_2) in Cylinders 99.9992 % Quality[5]

C28 Specifications and Guidelines for Hydrofluoric Acid[5]

C31 Specification for Methanol[5]

[1] This test method is under the jurisdiction of ASTM Committee F01 on Electronics and is the direct responsibility of Subcommittee F01.06 on Silicon Materials and Process Control.

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[2] *Annual Book of ASTM Standards*, Vol 11.01.

[3] *Annual Book of ASTM Standards*, Vol 14.03.

[4] *Annual Book of ASTM Standards*, Vol 10.05.

[5] Available from Semiconductor Equipment and Materials International, 3081 Zanker Road, San Jose, CA 95134 (www.semi.org).

3. Terminology

3.1 *Definitions:*

3.1.1 *four-point probe*—an electrical probe arrangement for determining the resistivity of a material in which separate pairs of contacts are used (1) for passing current through the specimen and (2) measuring the potential drop caused by the current.

3.1.1.1 *Discussion*—It may consist of a unitized probe head holding all four probes or it may have each of the four individual probes attached to a separate cantilevered arm.

3.1.2 *probe head, of a four-point probe*—the mounting that (1) fixes the position of the four-point probe in a specific pattern such as an in-line (collinear) or square array and (2) contains the pin bearings and springs or other means for applying a load to the probe pins.

3.1.3 *probe pin, of a four-point*—one of the four needles supporting the probe tips; mounting in a bearing contained in the probe head and loaded by a spring or dead weight.

3.1.4 *probe tip, of a four-point probe*—the part of the pin that contacts the wafer.

3.1.5 *probe tip spacing, of a four-point probe*—the distance between adjacent probe tips.

3.1.6 *sheet resistance, R_s* [Ω or Ω per square]—of a semiconductor or thin metal film, the ratio of the potential gradient (electric field) parallel with the current to the product of the current density and thickness.

3.1.6.1 *Discussion*——The sheet resistance is formally equal to the bulk resistivity divided by the thickness of the material, taken in the limit as the thickness approaches zero.

4. Summary of Method

4.1 A in-line four-point probe is used to determine the specimen sheet resistance.[6] A direct current is passed through the specimen between the outer probe pins, and the resulting potential difference is measured between the inner probe pins. The sheet resistance is calculated from the ratio of the measured voltage to current values using correction factors appropriate to the geometry.

4.2 The spacing between the probe tips is determined from measurements of indentations made by the probe tips in a polished silicon surface. This test is also used to determine the condition of the probe tips.

4.3 The accuracy of the electrical measuring equipment is tested by means of an analog circuit containing a known resistance together with other resistors that simulate the resistance at the contacts between the probe tips and the semiconductor surface.

5. Significance and Use

5.1 The sheet resistance of silicon epitaxial, diffused, and implanted layers is an important materials acceptance and process control parameter. The sheet resistance measurement may be used by itself or may be combined with a value of layer thickness, obtained separately, to obtain an estimate of the resistivity of an epitaxial layer or of the surface concentration of dopant for diffused layers.

5.2 This test method is suitable for use in materials acceptance, manufacturing control, research, and development.

NOTE 4—An alternate method, Test Method F 1529, will generally provide superior measurement precision that may be very important for spatial uniformity mapping requirements. That test method will also avoid the need to apply a lateral geometry correction to the measurements. However, that test method will generally require the use of a fully automated four-probe measurement system.

6. Interferences

6.1 Photoconductive and photovoltaic effects can seriously influence the observed resistivity, particularly with nearly intrinsic material. Therefore, all determinations should be made in a dark chamber unless experience shows that the material is insensitive to ambient illumination.

6.2 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.

6.3 Minority carrier injection during the measurement can occur due to the electric field in the specimen. With material possessing long lifetime of the minority carriers and high resistivity, such injection can result in a lowering of the resistivity for a distance of several centimeters from the point of injection. Carrier injection can be detected by repeating the measurements at lower current. In the absence of injection, no increase in resistivity should be observed at the lower current. The current level recommended (Table 1) should reduce the probability of difficulty from this source to a minimum, but in cases of doubt the measurements of 12.4 through 12.8 should be repeated at a lower current. If the proper current is being used, doubling or halving its magnitude should cause a total change in observed resistance which is less than 0.5 %.

6.4 Semiconductors have a significant temperature coefficient of resistivity. Consequently, the current used should be small to avoid resistive heating. The current level recommended (Table 1) should reduce the chances of this difficulty. If resistive heating is suspected, it can be detected by a change in readings as a function of time starting immediately after the current is applied. If such a change is observed, repeat the measurements of 12.4 through 12.8 at a lower current.

TABLE 1 Current Values Required for Measurements of Sheet Resistance

Sheet Resistance, Ω	I [A]
2.0–25	10 mA
20–250	1 mA
200–2500	100 µA
2000–25 000	10 µA

[A] The proper value of current depends on layer thickness and probe spacing in addition to layer sheet resistance. The current used shall be stable to within 0.05 % during the time of measurement and shall be selected to give a measured specimen voltage between 5 and 20 mV, inclusive. The overlap in ranges in the table is intentional since the table illustrates starting points for current selection.

[6] Smits, F. M., "Measurement of Sheet Resistivities with the Four-Point Probe," Bell System Technical Journal, BSTJA, Vol. 37, 1948, p. 711; Swartzendruber, L. J., "Correction Factor Tables for Four-Point Probe Resistivity Measurements on Thin, Circular Semiconductor Samples, NBS Technical Note 199, NBTNA, April 15, 1964.

6.5 Vibration of the probe head may cause variations in contact resistance, which is often manifested in unstable readings. If difficulty is encountered, the apparatus should be shock mounted.

6.6 Penetration of either current or voltage probe tip through the layer to be measured to the substrate can result in erroneous readings. This can usually be checked by mounting the specimen in direct contact with a metallic support grounded to the current supply and looking for a reduction in measured specimen voltage in at least one polarity. If this condition obtains, examine the probe tips microscopically for sharp asperities and remove these by polishing, or reduce probe force, or obtain probe pins with blunter tips.

6.7 The accuracy with which the separation of the probe tips is measured affects the accuracy of the calculated sheet resistance. The relative accuracy of probe tip spacing measurement decreases as the nominal value of the probe tip spacing decreases. For referee measurement purposes, use of a four-point probe with 1.59 mm (0.0625 in.) nominal spacing is required. Four-point probes having other nominal probe tip spacings are suitable for nonreferee measurements.

6.8 The accuracy of the final calculated value of sheet resistance is degraded if the four-point probe is not placed at the center of the specimen during measurement (see 12.4). For referee measurements, the center of the tip array probe shall not be more than 1.0 mm from the center of the specimen as measured along a nonflatted diameter.

6.9 The sheet resistance value calculated from the measurements may be in error if the thin film intended for the front surface is also formed on the rear surface of the wafer, and if the wafer edges provide a conducting path between the front-surface and rear-surface films. The effect of complete coverage of the wafer front surface, edge, and rear surface by a thin conducting film is to make the appropriate value of the correction factor F_2 equal to the limiting value of 4.532, regardless of wafer diameter or probe spacing. It is generally difficult or impossible to test for the conductivity type of the wafer edges. However, if a conductivity-type test of the rear surface of the wafer shows this surface to be of the same conductivity type as the front surface, the resulting sheet resistance measurements may be in error. The absolute value of the maximum error is given by $\frac{|F_2 - 4.532|}{F_2}$.

7. Apparatus

7.1 *Specimen Preparation*:

7.1.1 *Chemical Laboratory Apparatus*, such as plastic beakers, graduates, and plastic-coated tweezers suitable for use both with acids (including hydrofluoric) and with solvents. Adequate facilities for handling and disposing of acids and their vapors are essential.

7.1.2 *Ultrasonic Cleaner*, of suitable frequency (18 to 45 kHz) and adequate power.

7.2 *Measurement of Specimen Geometry*:

7.2.1 *Means for Measuring Specimen Diameter*, such as a micrometer or vernier caliper.

7.3 *Probe Head*:

7.3.1 *Probe Pins*:

7.3.1.1 *For Specimen Layers Having Thickness of 3 µm or Less*—Probe pins shall have blunt conical tips of a durable material such as tungsten carbide, with included angle in the nominal range from 45 to 150°. The probe tips shall terminate in a hemisphere with a radius in the nominal range from 100 to 250 µm, or in a flat circular truncation with a circle radius in the nominal range from 50 to 125 µm.

7.3.1.2 *For Specimen Layers Having Thickness Greater Than 3 µm*—Probe pins shall have sharp conical tips of a durable material such as tungsten carbide, with included angle in the nominal range from 45 to 150°. The probe tips shall terminate in a hemisphere with a radius in the nominal range from 35 to 100 µm.

7.3.2 *Probe Force*— For hemispherical-tipped probe pins with tip radius greater than 100 µm or for flat-tipped probe pins with tip radius greater than 50 µm, the force on each probe tip shall be in the range from 0.30 to 0.80 N (31 to 81 gf), inclusive, when the four-point probe is against the specimen in measurement position. For hemispherical-tipped probe pins with tip radius less than 100 µm, the force on each probe tip shall be 0.30 ± 0.03 N (31 ± 3 gf), inclusive, when the four-point probe is against the specimen in measurement position.

NOTE 5—The combination of probe tip radius and probe pin load, which is chosen, affects not only the immunity from probe tip penetration of very thin layers but also the electrical quality of contact and hence the noise and accuracy of measurement. The presence of higher resistivity values at the top surface of the silicon layer to be measured may require an increase in the force of probe pin or use of sharper probe tips. An example of this situation is a buried peak boron implant.

7.3.3 *Insulation*—The electrical isolation between a probe pin (with its associated spring and external lead) and any other probe pin or probe head part shall be at least $10^9 \Omega$.

7.3.4 *Probe Alignment and Separation*—The four-point probe tips shall be in an equally spaced linear array. The separations between adjacent probe tips shall have a nominal value of 1.59 mm (0.0625 in.). (Other nominal probe spacings such as 1.0 and 0.6 mm (0.040 and 0.025 in.) are suitable for nonreferee measurements.) The spacing between probe pins shall be determined in accordance with the procedure in 11.1 in order to establish the suitability of the probe head as defined in 11.1.3. The following apparatus is required for this determination:

7.3.4.1 *Piece of Material*, such as porous silicon or germanium that is softer than single crystal silicon, for use with blunt probes, and a slice or block of silicon for use with sharp probe tips as designated for layers more than 3–µm thick. In each case the surface of the piece of material must be polished and have a flatness characteristic of semiconductor wafers used in microelectronic device fabrication. The surface must have lateral dimensions adequate to span the outermost of the probe tips.

7.3.4.2 *Micrometer Movement*, capable of moving the probe head or silicon surface in increments in the nominal range from 0.05 to 0.10 mm in a direction perpendicular to a line through the probe tips and parallel to the plane of the surface.

7.3.4.3 *Toolmaker's or Other Traveling Microscope*, capable of measuring increments of 2.5 µm.

7.3.4.4 *Microscope*, with a magnification of at least 600× with an eyepiece magnification no greater than 15×.

7.4 *Specimen and Probe Pin Supports*:

7.4.1 *Specimen Support*— A copper block at least 100 mm (4 in.) diameter and at least 40 mm (1.6 in.) thick, or a rectangular block of equivalent mass and thickness, shall be used to support the specimen and provide a heat sink. For adequate heat transfer, vacuum clamping or other means for rigidly clamping the specimen to the heat-sink is necessary. The heat sink shall contain a hole that can accommodate a thermometer (see 7.5) in such a manner that the center of the bulb of the thermometer is not more than 10 mm below the central area of the heat-sink where the specimen will be placed (see Fig. 1). Comparable provision for the installation of a thermocouple, thermistor or resistane temperature detector (RTD) be made instead. An insulating disk, less than 0.076 mm thick and suitably perforated, shall be placed over the center area of the copper to provide electrical isolation between the specimen and the heat sink. Mineral oil or silicone heat sink compound shall be used between the insulating disk and the copper block to reduce the thermal resistance. The heat sink shall be arranged so that the center of the four-probe array can be placed within 1.0 mm of the center of the specimen (see 12.4). The heat-sink shall be connected to the ground point of the electrical measuring apparatus (see 7.6). The heat-sink shall be at a temperature of 23 ± 1°C during measurement.

NOTE 6—Shallow rings, concentric with the center of the copper block, may be machined into the heat sink in order to assist in rapid centering of specimens.

7.4.2 *Probe Assembly Support*—The probe head support shall allow the probe pin to be lowered onto the surface of the specimen with no evidence of lateral movement of the probe tips as observed under a magnification of at least 600× using an eyepiece having a magnification no larger than 15×.

7.5 *Thermometer*— ASTM Precision Thermometer having a range from − 8 to 32°C inclusive and conforming to the requirements for Thermometer 63C as prescribed in Specification E 1. The thermometer hole shall be filled with mineral oil or silicone heat sink compound to provide good thermal contact between heat sink and thermometer.

7.5.1 A thermocouple, thermistor or RTD known to be accurate to at least 0.1°C over the range of normal room temperatures may be mounted, instead of the glass bulb thermometer, in a comparable location in the heat sink.

7.6 *Electrical Measuring Apparatus*:

7.6.1 Any circuit that meets the requirements of 11.2 may be used to make the electrical measurements. The recommended circuit, connected as shown in Fig. 2, consists of the following:

7.6.1.1 *Constant-Current Source*—The value of current to be used depends on the layer sheet resistance and shall be selected so that the potential difference across the inner probes is between 2 and 60 mV. Currents between 10^{-6} and 10^{-2} A are required if the sheet resistance range 1 to 25 000 Ω inclusive is to be covered (Table 1).

7.6.1.2 *Double-Pole, Double-Throw Current-Reversing Switch*.

7.6.1.3 *Standard Resistor*, selected so as to yield a potential difference which is in the range from 0.1 to 10 times the potential difference measured across the layer when using the appropriate current value for the layer. Recommended resistances for various layer sheet resistance ranges are given in Table 2. Such a standard resistor is not needed when using a precision current supply that is known to have an output accuracy of 0.1 % or better of the nominal set point value for the measurement being made.

7.6.1.4 *Electronic Voltmeter*—To read the potential drop in volts or (when calibrated in conjunction with the current source) to read the volt-current ratio directly. The instrument shall be capable of measuring potential differences between 10^{-3} V and 10^{-1} V full scale and be able to resolve increments as small as 0.1 % of reading for each range, and must have a d-c input resistance of 100^{9}Ω or greater.

7.6.2 *Analog Test Circuit*—Five resistors connected as shown in Fig. 3 shall be used in testing the electrical measuring apparatus in accordance with the procedure given in 11.2. The resistance of the central resistor, *r*, shall be selected according to the sheet resistance of the layer to be measured as listed in Table 2.

7.7 *Conductivity-Type Determination*—Apparatus in accordance with Method A of Test Method F 42.

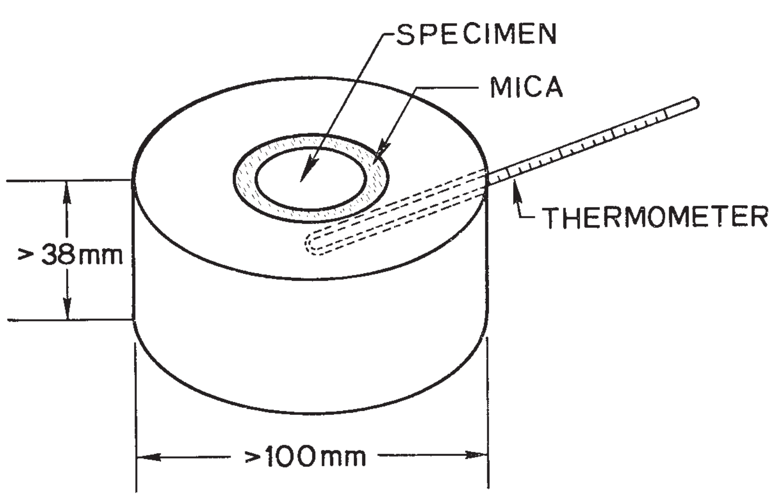


FIG. 1 Heat Sink with Specimen, Mica Insulator, and Thermometer

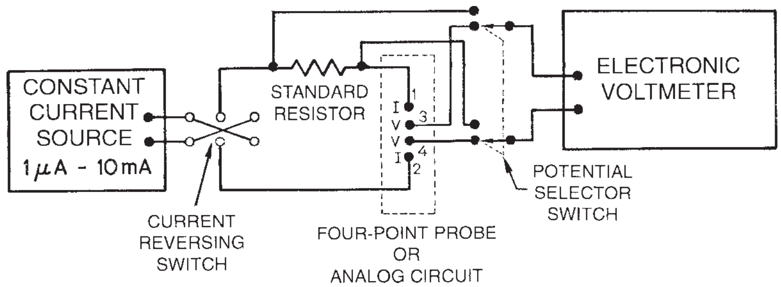


FIG. 2 Recommended Electrical Circuit

TABLE 2 Sheet Resistance Range Appropriate to Analog Test Circuit Resistance, r, and Recommended Standard Resistance, R_s, Values

Sheet Resistance, Ω	Analog and Standard Resistor, Ω [A]
2.0–25	10
20–250	100
200–2500	1000
2000–25 000	10 000

[A] The resistance shall be within a range from one half to twice the nominal value given, inclusive, and shall be known to ±0.05 %. The value of the standard resistor, *r* (Fig. 3), should be chosen to yield a voltage drop comparable to that measured across the specimen.

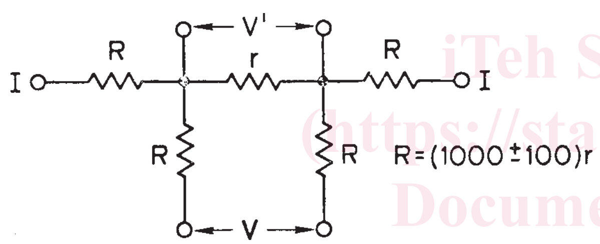


FIG. 3 Analog Test Circuit to Simulate Four-Point Probe Measurement

7.8 *Ohmmeter*, capable of indicating any leakage resistance up to $10^9 \Omega$.

8. Reagents and Materials

8.1 *Purity of Reagents*—All chemicals for which such specifications exist shall conform to the assay and impurity levels of Grade 1 SEMI specifications for the appropriate chemical. Other grades may be used provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

8.2 *Purity of Water*— Reference to water shall be understood to mean Type E-3 or better water as described in Guide D 5127.

8.3 *Dry Nitrogen* in accordance with SEMI C3.15.

8.4 *Hydrofluoric Acid* (HF), 49.0 ± 0.25 %, in accordance with SEMI C28.

8.5 *Insulator*, 0.076 mm (0.003 in.) thick or less (See 7.4.1).

8.6 *Methanol* (CH_3OH), in accordance with SEMI C31.

8.7 *Mineral Oil or Silicone Heat Sink Compound*.

9. Hazards

9.1 The chemicals used in this test method are potentially harmful and must be handled in an acid exhaust hood, with utmost care at all times.

9.2 **Warning**—Hydrofluoric acid solutions are particularly hazardous. They should not be used by anyone who is not familiar with the preventive measures and first aid treatment given in the appropriate Material Safety Data Sheet.

9.3 Constant-current power supplies are capable of producing high voltages if not connected to an external circuit. Therefore any changes of connection to a constant-current supply should be made either with the current supply turned off or with its output short-circuited.

10. Suitability of Test Specimen

10.1 Determine the average specimen diameter by measuring individual specimen diameters as follows. For specimens that are expected to be more than 51 mm (2 in.) in diameter, measure the length of three diameters at angular separations of 50 to 70°; for specimens that are expected to be between 32 and 51 mm (1.25 and 2.0 in.) in diameter, measure five diameters at angular separations of 30 to 45°. For specimens smaller than 32 mm in diameter, measure ten diameters at angular separations of 15 to 20°. Do not measure along any diameter that intersects an orientation notch or flat. Calculate the simple arithmetic average of these measurements, $\bar{D}$. For the specimen to be suitable, $\bar{D}$ must be greater than 10 times the average probe spacing, $\bar{S}$ (see 11.1.2.4), and the sample standard deviation of the diameter measurements shall be less than ($\bar{D}$/5 $\bar{S}$) % of $\bar{D}$. Record the value of $\bar{D}$.

10.2 Determine the conductivity type of the layer to be measured and the substrate of the specimen according to Method A of Test Methods F 42 if conductivity types are unknown. Follow the procedure as given in Test Method F 42 except that the surfaces shall be cleaned in accordance with 12.2 of this test method. The layer and substrate must be of opposite conductivity type in order to make sheet resistance measurements.

11. Suitability of Test Equipment

11.1 *Probe Head*—Establish the spacing between probe pins and probe tip condition in the following manner immediately prior to each referee test.

NOTE 7—This test procedure need be performed only once even if several specimens are to be measured during a single referee test.

11.1.1 *Procedure*:

11.1.1.1 Make a series of indentations of the probe tips on a polished silicon surface or other polished surface (depending on the sharpness of the probe tips, see 7.3.4.1) with the four-point probe. Make these indentations by applying the probe tips to the surface using loads as specified in 7.3.2. Lift the probe pins and move either the chosen polished surface or the probe head 0.05 to 0.10 mm in a direction perpendicular to the line through the probe tips. Again apply the probe tips to the polished surface. Repeat the procedure until a series of ten indentation sets is obtained.

NOTE 8—It is recommended that the silicon specimen or the probe tips be moved twice the usual distance after every second or third indentation set in order to assist the operator in identifying the indentations belonging to each set.

11.1.1.2 Ultrasonically degrease the specimen in acetone, rinse with methanol, and let dry. Place the specimen in a pliable plastic beaker during ultrasonic agitation in order to reduce the risk of breakage.

11.1.1.3 Place the chosen polished specimen on the stage of the toolmaker's microscope so that the *Y*-axis readings (Y_A and Y_B in Fig. 4(*a*)) do not differ by more than 0.15 mm (0.006 in.). For each of the ten indentation sets record the readings *A* through *H* (defined in Fig. 4(a)) on the *X*-axis of the toolmaker's microscope and the readings Y_A and Y_B on the *Y*-axis. These data should be recorded to the nearest 2.5 µm (0.0001 in.). Use a data sheet similar to that shown in Fig. 5.

11.1.1.4 Examine the indentations for continuity of the contact region and evidence of horizontal motion under a microscope of at least 600× magnification.

11.1.2 *Calculations*:

11.1.2.1 For each of the ten sets of measurements calculate the separations, S_{1j}, S_{2j}, S_{3j}, between adjacent probe tips as follows:

$$S_{1j} = [(C_j + D_j)/2] - [(A_j + B_j)/2], \tag{1}$$

$$S_{2j} = [(E_j + F_j)/2] - [(C_j + D_j)/2], \text{ and}$$

$$S_{3j} = [(G_j + H_j/2] - [(E_j - .F_j)/2].$$

In Eq 1 the index *j* is the indentation set number and takes the values 1 through 10.

11.1.2.2 Calculate the average value for each of the three probe tip spacings as follows, using the S_{ij} calculated above:

$$\bar{S}_i = (1/10)\Sigma_{j=1}^{10} S_{ij}, \tag{2}$$

where the index *i* takes the values 1, 2, 3 and record S_1, S_2, and S_3 in the appropriate box of a table such as that shown in Fig. 5.

11.1.2.3 Calculate the sample standard deviation, s_i, for each of the three spacing between probe pins using the $\bar{S}_i$ calculated from Eq 2, and the S_{ij} calculated from Eq 1, and the equation:

$$S_{3j} = [(G_j + H_j)/2] - [(E_j - F_j)/2] \tag{3}$$

11.1.2.4 Calculate the average probe pin spacing, $\bar{S}$, for the four-point probe:

$$\bar{S} = (1/3)(\bar{S}_1 + \bar{S}_2 + \bar{S}_3). \tag{4}$$

11.1.2.5 Calculate the probe pin spacing correction factor, F_{sp}:

$$F_{sp} = 1 + 1.082[1 - (S_2/S)] \tag{5}$$

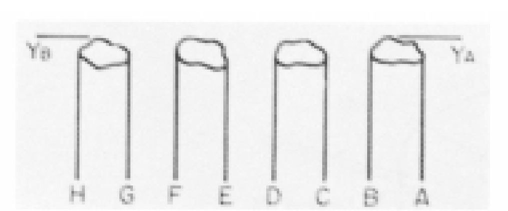
11.1.2.6 For a referee test, record results of all above calculations on a data sheet such as that shown in Fig. 5.

11.1.3 *Requirements*— For the probe head to be acceptable, it must meet the following requirements:

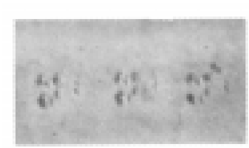
11.1.3.1 The set of ten measurements for each of the $\bar{S}_i$ shall have a sample standard deviation s_i not more than 0.3 % of $\bar{S}_i$. (For a four-point probe with nominal 1.59-mm (0.0625-in.) spacing, this is equivalent to $s_i \leq 4.7$ µm.)

11.1.3.2 The individual average separations ($\bar{S}_1$, $\bar{S}_2$, and $\bar{S}_3$) shall not differ by more than 2 % of the overall average, $\bar{S}$ (see 11.1.2.4).

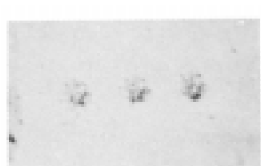
11.1.3.3 The indentations obtained should show only a single area of contact for each probe tip when examined under a microscope having a magnification of at least 600 × (Fig. 4).



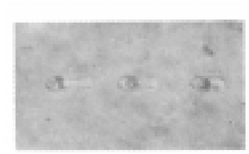
(*a*) Measurement Locations



(*c*) Photograph Showing Three Indentations of a Badly Worn Tip



(*b*) Photograph Showing Three Indentations of a Satisfactory Tip



(*d*) Photograph Showing Three Indentations of a Probe Tip which Moved Laterally on Contact With the Specimen Surface

NOTE 1—The indentations are 0.05 mm apart.

FIG. 4 Typical Probe Tip Indentation Pattern