Designation: F 672 – 88 (Reapproved 1995)$^{\epsilon 1}$

AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428
Reprinted from the Annual Book of ASTM Standards. Copyright ASTM

Standard Test Method for Measuring Resistivity Profiles Perpendicular to the Surface of a Silicon Wafer Using a Spreading Resistance Probe [1]

This standard is issued under the fixed designation F 672; 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.

ϵ^1 NOTE—Keywords were added editorially in January 1995.

INTRODUCTION

The measurement of resistivity profile by means of a spreading resistance probe is a complex procedure, with a number of commonly accepted options for carrying out the component measurements. ASTM Committee F-1 on Electronics has designed this test method to allow a range of choices, consistent with good practice, for the electronic configuration, type of specimen preparation, and method for measuring bevel angle. Items not specified by this test method are to be agreed upon by the parties to the test, usually from a specified set of choices in the context of a general restriction. The measurement of bevel angle is particularly difficult to specify, as the selection of an appropriate method depends not only on the range of angle measured but also on the quality of the instrumentation available for that method. Although ideally the beveled surface and the original surface should be two planes intersecting along a straight line, the actual geometry may differ from this ideal, further complicating the measurement. These points are recognized in the section on interferences and in Appendix X1 and associated references on the bevel-angle measurement.

1. Scope

1.1 This test method covers measurement of the resistivity profile perpendicular to the surface of a silicon wafer of known orientation and type.

NOTE 1—This test method may also be applicable to other semiconductor materials, but feasibility and precision have been evaluated only for silicon and germanium.

1.2 This test method may be used on epitaxial films, substrates, diffused layers, or ion-implanted layers, or any combination of these.

1.3 This test method is comparative in that the resistivity profile of an unknown specimen is determined by comparing its measured spreading resistance value with those of calibration standards of known resistivity. These calibration standards must have the same surface preparation, conductivity type, and crystallographic orientation as the unknown specimen.

1.4 This test method is intended for use on silicon wafers in any resistivity range for which there exist suitable standards. Polished, lapped, or ground surfaces may be used.

1.5 This test method is destructive in that the specimen must be beveled.

1.6 Correction factors, which take into account the effects of boundaries or local resistivity variations with depth, are needed prior to using calibration data to calculate resistivity from the spreading resistance values.

NOTE 2—This test method extends Method F 525 to depth profiling.

NOTE 3—This test method provides means for directly determining the resistivity profile of a silicon specimen normal to the specimen surface. Unlike Method F 84 and Test Methods F 374 and F 419, it can provide lateral spatial resolution of resistivity on the order of a few micrometres, and an in-depth spatial resolution on the order of 10 nm (100 Å). This test method can be used to profile through *p-n* junctions.

1.7 This test method is primarily a measurement for determining the resistivity profile in a silicon wafer. However, common practice is to convert the resistivity profile information to a density profile. For such purposes, a conversion between resistivity and majority carrier density is provided in Appendix X2.

1.8 *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:*

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

Current edition approved Oct. 31, 1988. Published December 1988. Originally published as F672 – 80. Last previous edition F672 – 87.

D 1125 Test Methods for Electrical Conductivity and Resistivity of Water [2]
E 1 Specification for ASTM Thermometers [3]
F 26 Test Methods for Determining the Orientation of a Semiconductive Single Crystal [4]
F 42 Test Method for Conductivity Type of Extrinsic Semiconducting Materials [4]
F 84 Test Method for Measuring Resistivity of Silicon Slices with an In-Line Four-Point Probe [4]
F 374 Test Method for Sheet Resistance of Silicon Epitaxial, Diffused, Polysilicon, and Ion-Implanted Layers Using an In-Line Four-Point Probe [4]
F 419 Test Method for Net Carrier Density in Silicon Epitaxial Layers by Capacitance Voltage Measurements on Fabricated Junction Schottky Diodes [4]
F 525 Test Method for Measuring Resistivity of Silicon Wafers Using a Spreading Resistance Probe [4]
F 674 Practice for Preparing Silicon for Spreading Resistance Measurements [4]
F 723 Practice for Conversion Between Resistivity and Dopant Density for Boron-Doped and Phosphorus-Doped Silicon [4]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *conducting boundary— for the purposes of this test method*, a boundary between two specimen layers of the same conductivity type taken to be the point at which the spreading resistance increases to twice the local minimum value it has in the layer of lower resistivity (Fig. 1*a*).

3.1.2 *effective electrical contact radius, a (cm)—of a spreading resistance probe assembly*, an empirical quantity defined by

$$a = (n\rho)/4R_s \qquad (1)$$

where:

n = number of current-carrying probes across which the potential drop is determined,
ρ = resistivity of a homogeneous semiconductor specimen, Ω·cm, and
R_s = measured spreading resistance, Ω.

3.1.2.1 *Discussion*—For a three-probe arrangement, $n = 1$; for a two-probe arrangement, $n = 2$.

3.1.3 *insulating boundary—for the purposes of this test method*, a boundary between two specimen layers of opposite conductivity type, taken to be the point at which the local maximum of the spreading resistance occurs (Fig. 1*b*).

3.1.4 *spreading resistance, R_s (Ω)—of a semiconductor*, the ratio of (*1*) the potential drop between a small-area conductive metal probe, and a reference point on the semiconductor, to (*2*) the current through the probe.

3.1.4.1 *Discussion*—This ratio, in fact, measures metal to semiconductor contact resistance as well as classical spreading resistance for a homogeneous specimen without electrical boundaries in the vicinity of the probes. For a specimen having resistivity gradients or electrical boundaries, this ratio also includes an effect due to those gradients or boundaries.

3.1.4.2 *Discussion*—In a three-probe arrangement, the experimental conditions approximate those of the definition (based on a single probe) and the spreading resistance is given by

$$R_s = V/I \qquad (2)$$

where:

V = potential drop between one of the current-carrying probes and the reference (non-current-carrying) probe on the front surface, mV, and
I = current through the metal probe, mA.

In a two-probe arrangement, the potential drop, V, is measured between two similar current-carrying metal probes. In this case, the voltage-to-current ratio, and hence the spreading resistance, is approximately twice that associated with a single probe.

3.1.5 *substrate—in semiconductor technology*, a wafer which is the basis for subsequent processing operations in the fabrication of semiconductor devices or circuits.

3.1.5.1 *Discussion*—The devices or circuits may be fabricated directly in the substrate or in a film of the same or another material grown or deposited on the substrate.

4. Summary of Test Method

4.1 A portion of the specimen wafer is beveled at an angle. The spreading resistance of a reproducibly formed point pressure contact (or contacts) is measured at a sequence of locations on the beveled surface. The spreading resistance may be measured using two, or three, probes (*1*) by applying a known constant voltage and measuring the current, (*2*) by applying a known constant current and measuring the voltage, or (*3*) by using a resistance comparator technique. A correction factor must be used **(1, 2, 3)** [5] which takes into account the effect of local resistivity gradients and boundaries on the finite sampling volume of the probes. The resistivity of the material immediately under the probes is then determined from a calibration curve derived from spreading resistance measurements made under the same conditions on calibration standards of known resistivity.

4.2 The following quantities are not specified by this test method and shall be agreed upon by the parties to the test:

4.2.1 Probe spacing, μm (7.3.1.3),

4.2.2 Sampling plan (10.1,

4.2.3 Minimum bevel length, mm, if required (11.1.1),

4.2.4 Bevel angle, deg, appropriate to the total depth of interest and desired resolution of the test specimen data (11.3 and Table 1),

4.2.5 Beveling technique (11.6),

4.2.6 Method for obtaining calibration curve (13.4),

4.2.7 Method for measuring bevel angle (14.10),

4.2.8 Probe spacing and probe step increment, μm, appropriate to the resolution desired along the profile of interest (13.2, 14.4),

[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] The boldface numbers in parentheses refer to the list of references at the end of this test method.

4.2.9 Algorithm for sampling volume correction factor (15.4), and

4.2.10 Conversion from resistivity profile to carrier density profile (see Appendix X3).

NOTE 4—Information relating the depth resolution and bevel angle for probe step increments of 5 and 10 µm and also bevel length to the layer thickness and bevel angle is given in Table 1. The probe step increment should be larger than the diameter of the specimen area damaged by the probes.

NOTE 5—Model data, of the type used to qualify participants in the round robin is provided in Annex A1. These are idealized data, free of measurement noise and contact calibration nonlinearity. They may be used to study the effects on a calculated resistivity profile of data round-off error or input measurement noise (if random or systematic noise is added to the model data). While they may be used to compare the results from different algorithms, such comparisons may be misleading. It has been found that some algorithms do a highly satisfactory analysis of certain real structures despite their relatively poorer performance on model data as described in Annex A1, (**4**). This is thought to be due to their relatively better ability to deal with measurement noise and with probe calibration nonlinearity.

5. Significance and Use

5.1 This test method can be used for process control, research and development, and materials acceptance purposes.

6. Interferences

6.1 *Temperature*—If the calibration and specimen measurements are not made at the same temperature, the accuracy of the results is likely to be adversely affected, as spreading resistance measurements are sensitive to the temperature of the specimen.

6.2 *Light*—Photoconductive and photovoltaic effects can seriously influence the resistance determined by this test method, especially on wafers having *p-n* junctions.

6.3 *Radiofrequency Fields*—If the apparatus is located near unshielded radiofrequency sources, the precision and accuracy of the results may be adversely affected, as spurious currents can be introduced in the measurement circuit in the presence of high-frequency fields.

6.4 *Mechanical Vibration*—If the apparatus is not sufficiently isolated from building-induced or other vibration sources, the precision and accuracy of the results may be adversely affected, as the probes are delicate (the entire probe assembly and the manner in which the probes contact the specimen surface are sensitive to shock and displacement).

6.5 *Minority Carrier Injection*—Caution should be taken to prevent minority carrier injection during the measurement. Experience has shown that if the potential applied between the current-carrying probes is kept to 20 mV or less, significant minority carrier injection should not occur.

6.6 *Reactive Atmosphere*—Exposure of the probe or specimen to reactive atmospheres, such as those produced in the vicinity of epitaxial reactors or by high humidity, may lead to changes in the characteristics of the instrument and to nonreproducible measurements. Probes and specimens shall be protected from such exposure. Relative humidity in excess of 60 % should be avoided.

6.7 *Semiconductor Surface*:

6.7.1 *Surface Instability*—It has been found that spreading resistance measurements made on surfaces that have been exposed to an aqueous solution may be erratic and nonreproducible. Surfaces exposed to solutions containing fluorine ions may also exhibit instability. The heat treatment included in the procedure (see 11.8) has been found to reduce these instabilities for *p*-type specimens **(5, 6).**

6.7.2 *Surface Damage*—Spreading resistance measurements made in areas of severe or nonuniform mechanical damage may give erroneous results. Such damage may be caused by previous spreading resistance probe marks, or by improper surface preparation.

6.7.3 *High Impurity Concentration*—At impurity concentrations greater than approximately 10^{20} cm^{-3} the defects caused by the impurity may have an effect on the measured spreading resistance. These defects and consequent effects may not be the same for all heavily doped specimens.

6.7.4 *Imperfect Bevel*—An ideal beveled surface is planar and intersects sharply along a straight line with a planar original surface of the specimen. Deviations from an ideal bevel can be caused by a number of factors such as nonuniform specimen thickness, specimen warp during mounting on the beveling block, rocking of the specimen mount during beveling, flexing or compression of the plate against which the beveling is done, and preferential attack of the beveling medium at the edge of the bevel. A non-ideal bevel may cause an incorrect bevel angle to be measured, present a changing depth scale along the line scanned by the probes, or both. Two simple limiting-case beveling defects can be described.

6.7.4.1 Bevel edge rounding is shown in Fig. 2. It is characterized by a gradual transition between the original and beveled surfaces of the specimen. It is found more likely to occur when a chem-mechanical beveling process is used, when a reciprocating motion is used during beveling, or when too soft a material is used for the polishing plate. Its existence is difficult to recognize by casual observation. Its presence can be seen, in general, when using bevel measurement methods 1, 3, or 4 in Appendix X1. The effect of this defect can be reduced if the specimen is covered with an oxide or nitride layer prior to beveling.

6.7.4.2 Bevel edge arcing is shown in Fig. 3. It is characterized by a curved or arced intersection of the original and beveled surfaces of the specimen, indicating that one or both surfaces are non-planar. However, a sharp transition from one surface to the other exists across the intersection. This defect is found more likely to occur when orbital motion is used during beveling, but if caused by a non-planar original surface on the specimen, it will occur regardless of motion used. This defect results in an inaccurate value of bevel angle with any measurement techniques (such as X1.1, X1.2, and X1.4 in Appendix X1) that sense an area of the specimen rather than scanning a line across the intersection.

6.7.5 *Deviation from Flatness* of the original surface, including the effects of stripping an anodic oxide layer that was applied to only a portion of the specimen (14.9), may adversely affect the precision of the measurement of bevel angle and therefore of the method.

6.8 *Correction Factor Assumptions*— All formulations of the correction factor assume the measurement is being made on a surface perpendicular to the impurity gradient. Also, the

assumption of lateral impurity uniformity is employed. Since neither of these assumptions is strictly true on a beveled surface, the corrected data may not represent the actual profile.

7. Apparatus

7.1 *Apparatus to Bevel the Test Specimen*:

7.1.1 *Lapping or Polishing Methods*—A mounting plug (beveling block) having the agreed-upon angle (see 4.2.4) and plug holder as shown in Fig. 4 and a flat plate of glass prepared in accordance with 6.1.1 of Practice F 674 or a flat plate of a suitable plastic such as methyl methacrylate.

7.1.1.1 *Polishing Machine*, if required, of the shaker, oscillating-tub, or rotary-plate type.

7.1.2 *Grinding Methods*—A motor-driven plastic or other soft-matrix wheel charged with diamond grit having a particle size of 3μ m or less.

7.2 *Means for Measuring Bevel Angle*, appropriate for the agreed-upon method (4.2.7, Appendix X1, and Fig. 5).

7.3 *Mechanical Apparatus*:

7.3.1 *Probes and Probe Assembly*—Spreading resistance probe assembly with provision for supporting and lowering either two or three replaceable probe tips to the wafer surface at a reproducible descent rate and with a predetermined static load. The supporting mechanism shall provide for lateral positioning of the probes for adjustment of the contact site, and for aligning the probes parallel the bevel edge to within± 2 μm (see 14.4.1).

7.3.1.1 *Probe Tips*—A hard, durable, low-resistivity substance that wears well without flaking, such as tungsten-osmium, tungsten-carbide, or tungsten-ruthenium alloys. The mechanical radius of curvature of the probe tips in the region that will touch the specimen shall be less than or equal to 25 μm. The tip angle of the probe shall be within the range from 30 to 60°, inclusive.

7.3.1.2 *Probe Loading and Descent Rate*— The loading applied to each point shall be in the range from 5 to 50 gf (49 to 490 mN), inclusive. A dashpot, or other means, for controlling the descent rate of the probes must be available if the load is applied by dead weight, but may not be necessary if the probes are spring-loaded (see 12.4).

NOTE 6—The sampling depth of the spreading resistance probes increases with increased probe loading, as does the risk of premature penetration to underlying layers. For best profile resolution, particularly for thin layers, probe loads should be kept in the low end of the above force range.

7.3.1.3 *Probe Spacing* shall be as agreed upon by the parties to the test.

NOTE 7—Since sensitivity of the measurement to the presence of lateral specimen boundaries (and sampling volume asymmetry resulting from the use of a beveled specimen) near the probe site is reduced with decreased probe spacing, the probe spacing should generally be as small as possible for the apparatus being used. Typical probe spacings are between 10 and 100 μm.

7.3.1.4 *Probe Insulation* to provide a d-c isolation resistance of 1 GΩ or greater between any pair of probes and between each probe and any guard circuit used.

7.3.2 *Specimen Holder*—Insulated vacuum chuck or other means for holding the specimen tightly while measurements are made (the mounting plug of 7.1.1 or an equivalent piece of apparatus may be used).

7.3.3 *Translation Microscope Stage*—Means for supporting, translating, rotating, and vertical adjustment of the specimen holder to facilitate alignment of probes and bevel edge. The stage shall provide translation position resolution of at least 1 μm. Gear boxes or stepper-motor drives for stage movement shall allow step intervals in the range from 1 to 100 μm per step, inclusive.

NOTE 8—Typical step intervals are 1, 2.5, 5, and multiples of 10 times these values.

7.4 *Vibration-Free Table* for supporting apparatus as required (see 6.4).

7.5 *Apparatus Enclosure* for providing darkened environment for spreading resistance measurements, if required by specimen material (see 6.2).

7.6 *Electrical Measuring Apparatus*—For a two-probe arrangement, use the apparatus of 7.6.1, 7.6.2, or 7.6.3. For a three-probe arrangement, use the apparatus of 7.6.2.

7.6.1 *Constant-Voltage Method* (see Fig. 6):

7.6.1.1 *D-C Voltage Source*, with a constant output between 1 and 20 mV, inclusive. The output potential shall be constant to ±0.1 % into a load that varies from 1 to 10 MΩ, inclusive.

7.6.1.2 *D-C Current Detector*, accurate to ±0.1 % and capable of measuring currents in the range from 10^{-10} to 10^{-2} A, inclusive, to three significant figures.

7.6.2 *Constant-Current Method* (see Fig. 7):

7.6.2.1 *Variable D-C Current Source*, capable of providing currents from 10^{-10} to 10^{-2} A, inclusive. The current output shall be accurate to ±0.1 %, stable at any output value to ±0.1 %, and capable of providing a current of 10^{-10} A into a 100 MΩ load. The current source shall have sufficient adjustment capability so that the specimen voltages which are measured remain in the range from 1 to 20 mV, inclusive, for all measurement points.

NOTE 9—The compliance voltage should not exceed 40 V for reasons of operator safety.

NOTE 10—For protection of the probes and specimen, capability should be provided for shorting the output when the probes are not in contact with the specimen, or else the compliance voltage should be reduced to 1 V or less.

7.6.2.2 *D-C Voltage Detector*, linear over the range from 1 to 50 mV, inclusive, capable of being read to three significant figures, and accurate to ±0.1 % of the reading. The input impedance shall be 1 GΩ or greater.

7.6.3 *Comparator Method* (see Fig. 8):

7.6.3.1 *D-C Voltage Source*, with a regulated output in the nominal range from 1 to 20 mV, inclusive, stable to ±3 % or better for a period of 1 min when connected to an external load in the range from 1 Ω to 100 MΩ.

7.6.3.2 *Log Comparator*, with an output proportional to the logarithm of the ratio of two currents (the logarithm of the ratio of the current, I_1, through the specimen to the current, I_2, through the standard resistor shall be directly measured by the circuitry). The comparator circuit shall contain a standard resistor, nominally 10 kΩ, which shall be known to an accuracy of ±0.1 %. The comparator shall be capable of measuring resistances from 1 Ω to 100 MΩ, inclusive, with a deviation from linearity of response not greater than ±1 %. If

the output is available as a voltage, at least two reference resistors, R_{r1} and R_{r2}, shall be supplied which can be selectively substituted for the specimen in the circuit (these resistors establish a fixed point and output voltage gain for use in calculating specimen spreading resistance from output voltage). The reference resistors shall be in the range from 1Ω to 100 MΩ, inclusive, and their values shall be known to an accuracy of at least ±1 %.

7.7 *Microscope*, capable of a magnification of at least 100× and a cross hair perpendicular to the direction of the microscope stage translation (7.3.3).

7.8 *Thermometer*— ASTM Precision Thermometer having a range from − 8 to + 32°C, inclusive, and conforming to the requirements for Thermometer 63C as described in Specification E 1.

7.9 *Means for Scribing and Breaking*— Customary means for scribing a silicon wafer and for breaking it into small pieces or dice.

7.10 *Etching Apparatus*, as required for removal of oxide or nitride layer (if present) from the specimen (14.4).

7.11 *Hot Plate*, capable of heating the specimen to a temperature of 150°C.

8. Reagents and Materials

8.1 *Reference Specimen Wafers for Calibration*, chosen in accordance with Section 13 from wafers in the resistivity range of the unknowns. The reference specimens shall be of the same conductivity type and nominal crystallographic orientation as the test specimens. The surface preparation technique used to produce the reference specimens shall match that of the test specimens; this includes preparation of the calibration specimens at a shallow bevel angle.

NOTE 11—It is desirable to use three or more reference specimens per decade of resistivity.

8.2 *Probe-Check Specimen*, consisting of *p*-type silicon and having a resistivity that is uniform to ± 15 %, as determined in accordance with Test Method F 525. This specimen shall have a nominal resistivity of 1 Ω·cm at 23°C. If the specimen is an epitaxial layer, the layer shall be at least 10 µm thick and fabricated on a substrate of the same conductivity type, and the surfaces shall be allowed to stabilize for at least 1 week subsequent to epitaxial growth. If the specimen is bulk silicon, the surface shall have been prepared by polish-etching followed by at least 1 week of aging, or by chem-mechanical polishing followed by thermal treatment of 150°C for 20 min in laboratory atmosphere. For use with a two-probe configuration, the chosen *p*-type specimen shall have a large-area ohmic contact fabricated into the rear surface of the specimen.

NOTE 12—It is desirable that the resistivity of the probe-check specimen be measured over a period of at least a month, to establish its history.

8.3 *Silicon Slice*, lapped or ground with 5-µm grit slurry, for conditioning the probe tips (see 12.5.2).

8.4 *Lapping, Polishing, or Grinding Materials*, as required for preparing the surfaces of the test specimen and calibration specimens (examples are alumina, garnet or diamond grit, and colloidal silica).

8.5 *Wax*, for mounting the test specimen to the beveling block and to the specimen holder.

8.6 *Solvent*—Methanol (CH_3OH) or other solvent recommended by the supplier of the diamond polishing medium.

8.7 *Distilled or Deionized Water*, having a resistivity greater than 2 MΩ·cm at 25°C as determined by the Nonreferee Method of Methods D 1125.

8.8 *Chemical Etch*, as required for removal of an oxide or nitride layer (if present) from the specimen (14.9).

9. Hazards

9.1 Use normal safety precautions in operating the electrical equipment.

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

10. Sampling

10.1 The sampling plan, including the definition of "lot" if sampling by lot is intended, shall be agreed upon by the parties to the test.

11. Test Specimen

11.1 Select an area of the silicon wafer on which the profile is desired.

11.1.1 Scribe and break or saw a small piece of the wafer. The minimum width (dimension nominally parallel to intersection of original and beveled surfaces) of the test specimen shall be at least 10 times the agreed-upon probe spacing, but not less than 3 mm. The minimum length of the specimen shall be not less than 2 mm plus the bevel length given in Table 1 for the agreed-upon bevel angle and for the layer thickness values given in the table. For layer thickness and bevel angle combinations other than those given in Table 1, the minimum specimen length shall be 2 mm plus an agreed-upon minimum bevel length.

NOTE 13—The entire wafer may be used if the beveling apparatus allows. However, it may be more difficult to obtain a uniform bevel on a large specimen.

11.2 On specimens to be beveled at angles below 30 min, deposit or grow a thin layer of SiO_2 or Si_3N_4 on the specimen surface. This can help to define the bevel edge. The thin layer must be removed prior to measurement of the bevel angle (14.9).

11.3 Select a mounting plug (beveling block) with the agreed-upon angle.

11.4 If the crystallographic orientation of the specimen surface is unknown, determine and record in accordance with Test Methods F 26 the orientation of the wafer from which the beveled specimen was cut.

11.5 Mount the test specimen on the mounting plug using the wax of 8.5.

11.6 Lap, grind, or polish the specimen to form a beveled area whose length is in accordance with 11.1.1, that is, sufficient to expose the total depth of interest (see 6.7.4, Table

1, Fig. 4) using the agreed-upon procedure selected from 11.6.1 through 11.6.5. Avoid severe, nonreproducible, or non-uniform mechanical damage. Hidden severe subsurface damage may remain if the bevel is formed by a coarse lapping or grinding technique followed by a cursory fine polishing method; do not use more than one stage of polishing, that is, use only one polishing medium on a given specimen.

11.6.1 *Chem-Mechanical Polishing*—Colloidal silica in a caustic aqueous solution; used on an acrylic plate.

11.6.2 *Aqueous Mechanical Polishing*—Aluminum oxide or garnet with a particle size of 1 µm or less in an aqueous slurry; used on a glass or acrylic plate.

11.6.3 *Non-Aqueous Mechanical Polishing*— Diamond in oil suspension, with particle size of 1 µm or less; used on an acrylic plate, or on a glass plate that has been lapped with 5 to 9-µm alumina and thoroughly cleaned prior to use for beveling.

11.6.4 *Lapping*—An aqueous slurry of aluminum oxide or garnet with particle size in the nominal range from 1 to 5 µm; used on a glass plate.

11.6.5 *Grinding*—Diamond grit of particle size 3 µm or less in a plastic or other soft matrix wheel. A non-aqueous liquid such as machinist's cutting oil shall be used with this test method.

11.7 Remove the residue of the polishing medium from the specimen using water for water-based polishing media and using methanol (or other solvent recommended by the supplier of the polishing medium) for non-aqueous-based polishing media.

11.8 If an aqueous polish was used, heat the specimen in air at 150 + 10°C for 15 ± 5 min. If the specimen is mounted in wax, be sure that the wax does not get on the bevel surface during this heat treatment. (Ground surfaces or surfaces prepared in the absence of aqueous solutions do not need heat treatment.)

NOTE 14—Freshly prepared surfaces should have a spreading resistance that is stable and repeatable for a long enough time so that the calibration standards need not be prepared freshly for each test run. The best long-term stability is achieved by a surface preparation that excludes aqueous or fluorine-containing solutions **(6).**

12. Preparation of Apparatus

12.1 Adjust the probe spacing to the agreed-upon value (see section 3.2.1), not to exceed 100 µm.

12.2 Choose a loading in the range from 5 to 50 gf (49 to 490 mN), inclusive, to be applied to the probes. In a multiple-probe arrangement, use the same loading for each probe.

NOTE 15—Reasonable loading for most profiling is 20 gf (195 mN).

12.3 Connect the appropriate electrical circuit (see Fig. 5, Fig. 6, and Fig. 7). If a voltage source is used (constant-voltage or comparator methods), adjust the potential to 20 mV or less. If a current source is used that has a compliance voltage greater than 1 V (constant-current method), short-circuit the output before measurement begins, and at all times when the probes are lifted from the specimen surface.

12.4 Adjust the descent rate of the probes onto the specimen to an appropriate value to minimize damage, and to ensure maximum measurement reproducibility.

NOTE 16—A nominal descent rate of 1 mm/s is generally adequate for a load of 20 gf (195 mN).

NOTE 17—It is generally possible to obtain 20 measurements with a scatter in the range from 1 to 5 % for most silicon specimens with a polished surface.

12.5 Make 20 measurements of the spreading resistance of the silicon probe-check specimen (8.2) in accordance with 14.6 through 14.11.

12.5.1 If the measured resistance is within ±20 % of the value assigned to the specimen, proceed to the tests in 12.6 and 12.7.

12.5.2 If the measured spreading resistance deviates by more than ±20 % from the value assigned to the probe-check specimen, either (*1*) replace the probes and repeat the test or (*2*) condition the probes by stepping them at least 500 times on a silicon substrate that has been ground with 5-µm grit slurry (see 8.3). Step the probes at least 20 times on a polished wafer such as the probe-check wafer and repeat the test.

NOTE 18—It is permissible to leave the slurry on the substrate during conditioning, but it must be removed from probe tips before measuring test specimens.

12.6 Using the microscope at a nominal magnification of 100×, examine the probe marks for reproducibility. If the probe marks from a given probe (*1*) do not appear similar, (*2*) do not have simple, near circular shape, or (*3*) show chipping or radial crack lines, decrease the descent rate, recondition the probe in accordance with 12.5.2, or replace the probe. Repeat 12.5 and 12.6.

NOTE 19—Experience suggests that the first approach should be decreasing the descent rate.

NOTE 20—Probe imprints from different probes need not be similar.

12.7 If the two-probe arrangement is being employed, verify that the spreading resistances of each of the two probes are equal to within 10 % when measured on the probe-check specimen (8.2).

12.7.1 Accomplish this measurement by using the ohmic rear-surface contact to replace each of the probes, in turn, and by measuring between the remaining probe and rear-surface contact in the normal manner (7.4). If the single-probe measurements do not agree within 10 %, recheck or adjust the loading (12.2) and descent rate (12.4) to be nominally equal on both probes. If satisfactory results are not achieved with equal probe loading and descent rate, recondition (12.5.1) or replace one or both probes. Repeat the tests given in 12.5, 12.6, and 12.7.

13. Calibration

13.1 Measure the resistivity of each of the specimens to be used as reference specimens (8.1), in accordance with Test Method F 84. Record the results.

13.2 Prepare each reference specimen in a manner identical to that intended for the test specimen, as described in Section 11. In accordance with 14.6 to 14.9, make a minimum of 20 spreading resistance measurements on the beveled surface of each of the proposed reference specimens. Make the measurements as close as possible to the region where the four-probe measurements were made. Use the agreed-upon probe-step increment that is to be used on the test specimen. Record the results. Using the thermometer (7.8), measure and

record the temperature in the vicinity of the measurement apparatus to the nearest ±1°C.

NOTE 21—The temperature of the specimen may not be the same as that of the surroundings if measurements are made very shortly after thermal treatment of the specimen or immediately following examination of the specimen illuminated by use of a high-intensity microscope illuminator.

13.3 Compute the mean of the 20 measurements made on each of the proposed reference specimens, and calculate the standard deviation for each set of measurements.

13.3.1 If the standard deviation of the spreading resistance measurements is greater than 10 % of the mean for a polished specimen (15 % for a lapped specimen), reprepare the specimen, and remeasure, or reject the specimen as a calibration reference specimen.

13.4 Using the resistivity value and the corresponding spreading resistance mean for each suitable calibration reference specimen, fit the agreed-upon curve (polynomial, piecewise-linear, or spline) to the calibration data for each conductivity type and orientation. Plot the data and calibration curve on graph paper.

NOTE 22—See Appendix X2 of Test Method F 419 for a computer program to generate a polynomial fit.

14. Procedure

14.1 Handle the specimen carefully to avoid contamination or damage to the surface.

14.2 Make all measurements at the same ambient temperature (±2°C) at which the calibration of 13.2 was done. Using the thermometer, measure and record the ambient temperature to the nearest± 1°C.

14.3 Determine, if unknown, the conductivity type of the layers present in accordance with Test Methods F 42.

14.4 Position the specimen on the specimen holder so that the probe or probes can be lowered to the desired measurement location near the bevel edge. Use the agreed-upon probe spacing and probe step increment (these values were also those used for the calibration procedure).

14.4.1 Align the specimen so that each of the probes of a multiprobe apparatus are aligned with the bevel edge to within ±2 µm. This can be accomplished by first aligning the probes to a reference crosshair in the microscope. Then align the specimen bevel edge to the same crosshair.

NOTE 23—It is recommended that the specimen be positioned so that the first five to ten steps be on the original, unbeveled surface.

14.5 Lower the probes to make contact with the specimen surface, and adjust the voltage or current source to within 0.1 % of the desired value (7.6.1.1, 7.6.2.1), unless the comparator method is being used (in which case the setting is not critical). Record, as appropriate, the constant-voltage setting as V, in millivolts or the constant-current setting as I, in milliamperes. If a constant-current source is used, remove the short circuit (12.3) so that the current now passes through the probes.

14.6 After a suitable settling period (usually about 1 s) measure and record the following quantities, as appropriate to the chosen measurement method: (*1*) the current, I, in milliamperes (constant-voltage method), (*2*) the voltage, V, in millivolts (constant-current method), and (*3*) either log $[I_1/I_2]$ or the output voltage, V, in millivolts, depending on the form of the output from the current comparator (current-comparator method).

14.7 Lift the probes from the specimen. If the constant-current method is being used, short-circuit the current source prior to lifting the probes. Move the specimen to the next position using the agreed-upon probe step increment.

14.8 Repeat 14.4 through 14.7, using nominally the same settling period as for the first measurement, until the desired number of measurements has been made.

14.9 If an oxide or nitride is present, remove this layer in accordance with customary chemical etching procedure.

14.10 Measure and record the angle, theta, between the beveled surface and the original surface using the agreed-upon method. Make this measurement in the same region of the specimen used for the spreading resistance measurements.

NOTE 24—Five different methods of making the measurement of bevel angle are identified and discussed in Appendix X1. See also 6.7.4 for a discussion of interferences related to bevel-angle measurement.

15. Calculation

15.1 Calculate the spreading resistance, R_s, in ohms, for each measurement position as follows:

15.1.1 *Constant-Voltage Method or Constant-Current Method*:

$$R_s = V/I \tag{3}$$

where:

V = applied voltage (constant-voltage method) or measured voltage (constant-current method), mV, and

I = measured current (constant-voltage method) or applied current (constant-current method), mA.

15.1.2 *Comparator Method*:

15.1.2.1 Output given directly as the logarithm of the current ratio:

$$R_s = R_0 \log (I_1/I_2) \tag{4}$$

where:

R_0 = resistance of the standard resistor, Ω, and

$\log (I_1/I_2)$ = output of the log comparator.

15.1.2.2 Output given as a voltage:

$$R_s = R_{r1}\, 10 \exp \left[(\log R_{r2} - \log R_{r1}) \left(\frac{V_s - V_1}{V_2 - V_1} \right) \right] \tag{5}$$

where:

R_{r1} = resistance of the smaller of the reference resistors, Ω ,

V_s = output voltage for measurement of the specimen, mV,

V_1 = output voltage for measurement of reference resistor R_{r1}, mV, and

V_2 = output voltage for measurement of reference resistor R_{r2}, mV.

15.2 Calculate the depth Z_N of each point N as follows:

$$Z_N = x(N - q) \sin \Theta \tag{6}$$

where:

Z_N = depth of the Nth point from the bevel edge, µ m,

q = fraction of the step increment between the bevel edge and the first point on the bevel.
x = agreed-upon probe step increment, µm, and
Θ = measured bevel angle, deg (14.10).

NOTE 25—The error delta Z_N in the calculated depth Z_N of the Nth point is given by:

$$\Delta Z_N = [(x (N - q) \Delta\Theta)^2 + (x\Delta q \sin\Theta)^2 + (\Delta x (N - q) \sin\Theta)^2]^{1/2}$$

The first term represents the contribution to the overall error from the error in angle measurement. The second term represents the contribution to the overall error from the uncertainty in the definition of the bevel edge (14.4.1). The third term represents the contribution to the overall error from the uncertainty in the setting of the probe step increment. As an example, for a 5-µm layer with a bevel angle of 34 min ($\sin \Theta = 0.01$) measured to ±5 %, a 10-µm probe step increment assumed to be accurate to ±0.1 µm, and an error in the definition of the bevel edge of ± 5 µm, the total error is

$$\Delta Z_N = [(0.005 (N - q))^2 + (0.05)^2 + (0.001 (N - q))^2]^{1/2}$$

The error in the first point is thus ±0.051 µm, and the error in the fiftieth point is ±0.505 µm.

15.3 Calculate and record the thickness of each layer in the test specimen, in accordance with the conducting and insulating boundary definitions of 5.1 and 5.3.

15.4 Use the agreed-upon sampling volume correction-factor algorithm to account for the finite thickness or graded nature, or both, of the layer being profiled in accordance with either 15.4.1 or 15.4.2.

15.4.1 *Multilayer or Local-Slope Algorithm*—Correct the spreading resistance values in accordance with either 15.4.1.1 or 15.4.1.2 and then generate a resistivity profile from the corrected spreading resistance profile in accordance with 15.4.1.3.

15.4.1.1 *Multilayer Correction Algorithm*—Correct the spreading resistance values in accordance with the method described in D'Avonzo et al (**1**), which gives a computer program written in FORTRAN IV for implementing a complete multilayer-model correction-factor algorithm.

NOTE 26—This calculation requires extensive computer time. The two-layer correction factors (15.4.2) are easier to calculate and, for the limiting cases of a uniform layer over a perfectly conducting or a perfectly insulating boundary, show agreement of better than 3 % with the multilayer correction factors for specimens in which the ratio of layer thickness to effective electrical contact radius is in the range from 0.1 to 100, inclusive.

15.4.1.2 *Local-Slope Correction Algorithm*—Correct the spreading resistance values in accordance with the method described in Dickey and Ehrstein (**2**), which gives a computer program written in BASIC to implement an efficient calculation of a sampling volume correction factor.

15.4.1.3 Using the calibration relation derived from specimens of the same crystallographic orientation, conductivity type, and surface preparation as the test specimen (13.4), determine the resistivity that corresponds to each value of the corrected spreading resistance.

15.4.2 *Two-Layer Correction Algorithm*—Using the calibration relation derived from specimens of the same crystallographic orientation, conductivity type, and surface preparation as the test specimen (13.4), determine the resistivity that corresponds to each value of the uncorrected spreading resistance. Correct these resistivity values in accordance with the methods described in Morris et al (**3**).

NOTE 27—Two-layer correction factors can be used only in monotonically increasing or decreasing distributions.

16. Report

16.1 Report the following information:
16.1.1 Specimen identification;
16.1.2 Identification of operator;
16.1.3 Date of test;
16.1.4 Quantities agreed upon by the parties to the test:
16.1.4.1 Probe spacing, µm,
16.1.4.2 Sampling plan,
16.1.4.3 Bevel angle, deg,
16.1.4.4 Minimum bevel length, if required, mm,
16.1.4.5 Beveling technique,
16.1.4.6 Method for obtaining calibration curve,
16.1.4.7 Method for measuring bevel angle,
16.1.4.8 Probe step increment, µm, and
16.1.4.9 Algorithm for sampling volume correction factor;
16.1.5 Loading on the probe tips, gf (or mN);
16.1.6 Crystallographic orientation of the specimen;
16.1.7 Conductivity type of layer(s) and substrate;
16.1.8 Thickness of layer(s), µm;
16.1.9 Ambient temperature, °C;
16.1.10 Surface preparation technique;
16.1.11 Spreading resistance profile of test specimen;
16.1.12 Resistivity profile of test specimen; and
16.1.13 Majority carrier density profile (if agreed to by parties to the test).

17. Precision and Bias

17.1 An estimate of precision is based on the results of the nine laboratories in a multilaboratory study. The specimen in this study was an emulation of a bipolar transistor structure having ion implanted emitter and base layers, an epitaxial collector, a diffused layer under the collector, and a substrate. This structure included junctions ranging in depth from about 0.6 to about 8 µm and resistivities ranging from about 0.001 to about 10 Ω·cm.

17.2 In this study, each laboratory was given three pieces of the test specimen and asked to take data using a separate piece on each of three days. On each day, one end of the specimen piece was to be prepared with a shallow bevel and data taken on the emitter, base, and collector layers; the other end of the piece was to be prepared with a steeper bevel angle and data taken all the way to the substrate.

17.3 Test data were included to detect differences in correction factor algorithms used. Differences among the laboratories were observed from this test data. Test specimens were included to test differences in probe response. No significant difference in probe response was observed. Each laboratory was requested to provide calibration data for the probe sets used. No common set of calibration material was available. Noticeable differences were seen in the reported calibration values.

17.4 Estimates of multilaboratory precision are given in Table A1.2 for a number of features of the test structure. These estimates are based on the averages of three measurements reported by the individual laboratories. No adjustments were made for differences in algorithms or calibration data at these

laboratories. The estimates are broken into two groups. The first group was obtained from five laboratories that used the same form of the multilayer data analysis algorithm; proprietary versions of the second group were obtained from four laboratories that used four different algorithms—two based on the“ local slope” model and two based on the multilayer model. Precision values (1 *s* %) are better than 5 % for junction location measurements and range from 16 to 28 % for layer resistivity minimum and sheet resistance values. Further description of the results is given in Annex A1.

18. Keywords

18.1 carrier density profile; profile; resistivity profile; spreading resistance; spreading resistance probe; spreading resistance profile; SRP

ANNEX

(Mandatory Information)

A1. DESCRIPTION OF ROUND ROBIN

A1.1 The round robin consisted of three preliminary tests and a bipolar transistor specimen which was measured and analyzed for multilaboratory precision. These three tests were as follows: (*1*) electrical qualification of probe performance, (*2*) mechanical qualification of probe imprint and bevel surface texture, and (*3*) algorithm qualification on three sets of model data.

A1.1.1 Electrical qualification of probe performance was done as follows: top surface measurements were made on specimens of 0.001Ω· cm and 1 Ω·cm *p*-type bulk silicon, and nominal 5Ω· cm, 1 µm thick n/n^+ epitaxial silicon using each of the probes separately and also using both probes together; to enable measurements with each probe separately the specimens were back-side soldered to a brass block which provided a measurement ground. Measurements on all three specimens were used to test for equivalence of response between the two probes being used, measurements on the 0.001-Ω·cm specimen were used to qualify the probes for acceptably low noise level, measurements on the 1-Ω·cm specimen (a traditional qualification specimen) were used to test for appropriateness of spreading resistance value at the stated probe load, and measurements on the epitaxial specimen were used to test for probe penetration. In addition, a specimen with a relatively high-fluence annealed arsenic implant was to be beveled and depth profiled twice, with the electrical polarity of the probes being reversed between the two sets of measurements. These profiles were examined for dynamic range of the data to the *n/p* junction and for equivalence of the profiles upon reversing polarity; this test served to qualify the probes for alignment and for probe penetration when in the vicinity of the junction.

A1.1.2 A bare piece of unspecified silicon was provided to each laboratory. This piece was to be beveled in the customary manner by each laboratory and about 30 sets of probe impressions at increments of at least 10 µm made on the top surface and extending onto the beveled surface. The specimen was returned to the coordinating laboratory for inspection of beveled surface quality and probe impression quality.

A1.1.3 Three sets of noise-free model data listings were supplied to each laboratory. They were obtained by taking the resistivity depth profiles appropriate to three different graded structures as input arrays to the multilayer algorithm of D'Avonzo et al **(1)** using the current distribution appropriate to a thick uniform specimen, and obtaining calculated spreading resistance arrays as outputs. These output arrays were analyzed by each participating laboratory using its resident algorithm to test whether the original resistivity depth profile arrays could be reproduced. The three sets of model data were simulations of the following: (*1*) a two peak high dose implant into a 100-Ω·cm substrate of the same conductivity, (*2*) the same two peak implant with junction isolation to the substrate simulated by a substrate resistivity of 10^8Ω· cm, and (*3*) a 10 Ω·cm, 1 µm thick epitaxial layer over a 0.05-Ω·cm substrate of the same conductivity.

A1.2 Sixteen laboratories submitted data to the round robin. Six were dropped from the final analysis for the following reasons: (*1*) one was dropped because of severely rounded specimen bevels (see Fig. 3) and for nonequivalence of probe response (see A1.1.1), (*2*) one was dropped because of very noisy profile data which correlated with a very rough beveled surface (A1.1.2), (*3*) one was dropped because of very noisy data on the test and qualification specimens, (*4*) one was dropped because its junction depth measurements were significantly deeper than all other labs, indicating a beveling or bevel angle measurement problem, (*5*) one was dropped for failing to provide analysis of the data and because the beveled qualification specimen showed significant evidence of probe penetration, and (*6*) one was dropped for completely failing to provide analyzed data.

A1.2.1 The remaining nine laboratories were considered to have passed the probe and bevel surface qualification tests of A1.1.1 and A1.1.2. Model data qualification of algorithms showed two distinct patterns, however. Five laboratories that used the same version of the multilayer algorithm produced resistivity profiles for both of the two-peak implant structures which were noticeably different from the starting resistivity profiles; these laboratories produced results that were the same as each other. The remaining four laboratories quite faithfully reproduced the resistivity profiles of both two-peak implants despite the fact that two of these laboratories used some form of the "local slope" algorithm, and the other two used proprietary versions of the“ multilayer” algorithm. None of the laboratories in either group faithfully reproduced the resistivity profile of the model n/n^+ structure. Most calculated the

epitaxial layer to be slightly graded rather than flat and to have a typical resistivity of about 8.5 rather than 10 Ω·cm. For analysis of multilaboratory precision of the real bipolar specimen data, the five laboratories that used the same multilayer algorithm were put in one group and the remaining four laboratories were put in a second group.

A1.2.2 All nine of these laboratories used either 0.1 or 0.25-μm diamond abrasive on glass to bevel the test specimen. A variety of values were used for probe load, probe separation, bevel angle, and measurement step increment. A summary of the range of values for some of these parameters is given in Table A1.1. In addition, one laboratory used tungsten carbide probes rather than tungsten-osmium as used by the other eight laboratories. A wide variety of probe calibration responses was reported.

A1.3 Table A1.2 gives a summary of measurement averages and precision from the two laboratory groups for the salient features of the test specimen. Resistivity minimum values for each of the layers as used for this summary were obtained by first fitting the reported resistivity values in the vicinity of the minimum to a quadratic function for each of the profiles; this had the effect of suppressing extraneous scatter due to slightly noisy data.

APPENDIXES

(Nonmandatory Information)

X1. FIVE METHODS OF MEASURING BEVEL ANGLE

X1.1 Reflection Method (7)

X1.1.1 This method covers angles for which the sine of the angle is at least 0.01, that is, for angles greater than about 34 min.

X1.1.2 Laser or other collimated light incident upon the intersection between the beveled surface and the original surface at the site of the spreading resistance measurements is reflected in two distinct beams, with a center-to-center separation distance, *S*, as measured at a distance *L*, from the specimen. For a selected *L*, *S* is measured on a suitable screen, positioned to be perpendicular to the bisector of the angle between the beams, and the results recorded in consistent units. The angle is calculated to be equal to one-half arcsin (*S*/*L*).

X1.1.3 The accuracy of this method may be affected adversely if the beams are not well collimated. Bevel edge rounding (Fig. 2) will tend to produce poorly defined or asymmetrically enlarged spots of light on the screen, and therefore also tend to degrade accuracy. Bevel edge arcing (Fig. 3), on the other hand, should have minimal effect on accuracy, especially if the spot size is small and the restriction on the angle measurement site followed.

X1.2 Small-Angle Measurement Method (8, 9)

X1.2.1 This method covers small angles, particularly those less than 34 min. The technique involves the superposition of line images reflected from the specimen's original surface and the beveled area.

X1.2.2 The procedure is given independently in each reference.

X1.2.3 Bevel edge arcing is likely to degrade accuracy, whereas bevel edge rounding is not.

X1.3 Profilometer Method

X1.3.1 A mechanical surface profilometer operated in accordance with the manufacturer's instruction manual is used to record a trace corresponding to the complete bevel profile, with the restrictions that the stylus traverse the site specimen adjacent to that of the spreading resistance measurements and cross the bevel edge at right angles to the local edge curvature.

X1.3.2 The method is primarily limited in accuracy by the accuracy of the horizontal drive of the profilometer. If the restrictions indicated in X1.3.1 are complied with, bevel edge arcing has little effect on accuracy. Average bevel angle can be measured despite bevel edge rounding, and approximate corrections for the effect of rounding can be determined graphically.

X1.4 Interferometric Method

X1.4.1 The method is described on pp. 99–108 of D'Avonzo et al (**1**). The method is considered to be versatile, but tedious.

X1.4.2 The accuracy of the method depends in large part on the interferometer selected; a multiple-pass type is recommended. Measurement accuracy may degrade significantly as a result of bevel edge arcing; bevel edge rounding should have little or no effect.

X1.5 Microscope Depth-of-Focus Method

X1.5.1 This method covers the measurement of angles greater than 34 min.

X1.5.2 The specimen is mounted on a mechanical microscope stage having the capability for precise translation of the specimen along a selected horizontal axis. At two points each on the original and beveled surfaces, selected to be along the line of the spreading resistance measurement sites, measurements are made of (*1*) position on the translation axis and (*2*) local height of the specimen above the stage reference plane, as determined by the operator's judgment of the plane of best focus and the microscope fine-focus control. The bevel angle is calculated on the basis of a simple geometrical algorithm.

X1.5.3 The accuracy and precision of this method depends in large part on the operator's judgment of the plane of best focus and on the ease and resolution with which the specimen local heights can be read from the microscope vertical scale. Typical limiting depth resolution available from a good-quality microscope is on the order of ±2 μm; an experienced operator

may be able to reduce this figure somewhat. Bevel edge arcing should not affect the measurement, provided the site restriction is followed; bevel edge rounding may tend to degrade accuracy, if local specimen height is measured in the rounded region of the bevel edge.

X1.5.4 *Procedure*:

X1.5.4.1 Mount the specimen on the microscope stage in such a manner that the translation axis of the stage is parallel to the path scanned by the probes and so that the region containing that portion of the path that is on the original surface is in the field of view of the microscope. Adjust the focus control of the microscope to bring the surface into good focus.

X1.5.4.2 Select a site on the original surface near the probe path at least 1.2 mm from the intersection of the two surfaces and adjust the mechanical stage controls until that site is at the center of the field of view, as determined visually. Be careful not to disturb the parallelism of the stage translation axis with respect to the probe tracks. Adjust the fine-focus control with care to bring the selected site into the best possible focus (it will probably be necessary to move through the plane of best focus several times in each direction in order to determine where that plane lies). Record the position of the stage and the microscope vertical scale reading. Designate these values as x_1 and z_1, respectively.

X1.5.4.3 Translate the stage parallel to the probe tracks to a second site on the original surface near the probe path at least 1 mm from the first and at least 0.05 mm from the intersection of the two surfaces and repeat X1.5.4.2 for this site, using the designations x_2 and z_2 for the stage position and fine-focus setting, respectively.

X1.5.4.4 In a similar manner, select the third and fourth sites to be near the probe path on the beveled surface, and record the position of the stage and the setting of the fine-focus control for each in turn as x_3, z_3 and x_4, z_4. Select the third site to be at least 0.05 mm from the intersection of the two surfaces and the fourth site to be at least 1 mm from the third.

X1.5.5 *Calculations*:

X1.5.5.1 If required, convert the recorded readings into consistent units.

X1.5.5.2 Select the configuration that applies from the three possible configurations illustrated in Fig. X1.1 *a*, *b*, *c*. Calculate the bevel angle, α, in accordance with Eq. for configuration *a*, for which z_3 is greater than z_4. Calculate the bevel angle in accordance with Eq. for configuration *b*, for which z_3 is less than z_4. Calculate the bevel angle in accordance with Eq Eq. for configuration *c*, for which z_3 is equal to z_4.

$$\alpha = \alpha_{12} + \alpha_{34}$$

where:

$$\alpha_{12} = \tan^{-1}\left(\frac{|z_2 - z_1|}{|x_2 - x_1|}\right), \text{ and}$$

$$\alpha_{34} = \tan^{-1}\left(\frac{|z_3 - z_4|}{|x_3 - x_4|}\right)$$

$$\alpha = \alpha_{12} - \alpha_{34} \quad \text{(X1.1)}$$

$$\alpha = \alpha_{12} \quad \text{(X1.2)}$$

X2. MODEL DATA FOR EVALUATING SPREADING RESISTANCE ANALYSIS ALGORITHMS

X2.1 Three arrays of model data are provided. All are based on the assumption of a two-probe spreading resistance apparatus with a radius of contact for each of the probes of 2 µm and a probe separation of 50 µm. They were obtained by the procedure described by Albers **(10)**.

X2.1.1 Two of the arrays are exactly as used in the multilaboratory test. They are the arrays for the following: (*1*) a two discrete-peak ion-implant into a 100-Ω·cm substrate of the same conductivity type and (*2*) a 1 µm thick 10-Ω·cm epitaxial layer over a 0.05-Ω·cm substrate of the same conductivity type. The model spreading resistance data for both these arrays were calculated assuming that the current distribution under the probes was that appropriate to a thick, uniform layer (the Schumann and Gardner assumption). The third model data array is also for a 1 µm thick 10-Ω·cm epitaxial layer over a 0.05-Ω·cm substrate, but it was calculated assuming that the current under the probes has a uniform density (the Choo assumption).

X2.1.2 These model data arrays are given in Table X2.1, Table X2.2, and Table X2.3, respectively.

X2.1.3 To use the model data, all pairs of measurement depth and log spreading resistance values for one of the structures are entered as input data to the spreading resistance analysis algorithm to be tested, along with an assumed contact radius of 2 µm and probe spacing of 50µ m. The model data are then analyzed and the resulting resistivity profile compared with that given in the listing of model data.

X2.2 For fixed values of probe separation and probe contact radius, the model spreading resistance values that are calculated from an assumed starting resistivity profile depend on the current distribution that is assumed to exist under the probes and on the particular algorithm (numerical procedure) that is used for the calculation. The model data given here were based on current distribution assumptions as stated for each set of data and were calculated using the algorithm of D'Avonzo et al **(1).** Their procedure was chosen because it uses a highly detailed numerical integration of the required equations and because it is fully documented.

X3. CONVERSION OF RESISTIVITY PROFILE TO CARRIER CONCENTRATION PROFILES

X3.1 Two relations are provided, one for *p*-type silicon and one for *n*-type silicon, to allow conversion of resistivity profiles derived from spreading resistance measurements to carrier density profiles. They are taken from the work of Thurber et al **(11)** and are based on the same set of data used for conversion of resistivity to dopant density in Practice F 723. These conversions are based on empirical studies of boron- and phosphorus-doped silicon and application to other dopant impurities in silicon must be done with caution.

X3.1.1 Boron-doped silicon less than or equal to 0.1 Ω·cm:

$$p = \frac{6.242 \times 10^{18}}{V\rho}$$

where:

$$V = \frac{482.8}{1 + \left(\frac{\rho}{0.0825}\right)^{-0.811}} + 52.4e^{-\left(\frac{\rho}{0.00409}\right)}$$

p = carrier density, cm $^{-3}$, and
ρ = resistivity, Ω·cm.

X3.1.2 Boron-doped silicon greater than 0.1 Ω·cm:

$$p = \frac{6.242 \times 10^{18}}{V\rho}$$

where:

$$V = \frac{482.8}{1 + \left(\frac{\rho}{0.0825}\right)^{-0.811}}$$

X3.1.3 Phosphorus-doped silicon:

$$n = \frac{6.242 \times 10^{18} \times 10^{V}}{\rho}$$

where:

$$V = \frac{A_0 + A_1X + A_2X^2 + A_3X^3}{1 + B_1X + B_2X^2 + B_3X^3}$$

where:
X = log (ρ),
A_0 = –3.1122,
A_1 = –3.3347,
A_2 = –1.261,
A_3 = –0.15701,
B_1 = 1.0463,
B_2 = 0.39941,
B_3 = 0.049746, and
n = carrier density, cm $^{-3}$.

X3.1.4 The silicon slices in the empirical study from which these conversion relations were derived, had a lowest resistivity value of 0.00086 Ω-cm for boron-doped silicon and 0.00055 Ω-cm for phosphorus-doped silicon. Caution should be taken when applying these conversion relations to resistivities near or below these values. In particular, due to independent data-fitting procedures in **(11)** for deriving carrier densities and dopant densities from resistivity values, it is found that for phosphorus-doped silicon below 0.0009 Ω-cm, a larger value will be calculated for carrier density using the above relation, than will be calculated for doping density using Practice F 723.

REFERENCES

(**1**) D'Avonzo, D. L., Rung, R. D., and Dutton, R. W.," Spreading Resistance for Impurity Profiles," Stanford University Technical Report No. 5013-2, February 1977.

(**2**) Dickey, D. H., and Ehrstein, J. R., *Semiconductor Measurement Technology: Spreading Resistance Analysis for Silicon Layers with Nonuniform Resistivity*, NBS Special Publication 400-48, May 1979.

(**3**) Morris, G. L., Langer, P. H., and White, J. C., *Semiconductor Measurement Technology:* Spreading Resistance Symposium, NBS Special Publication 400-10, J. R. Ehrstein, ed., December 1974, p. 63.

(**4**) Pawlik, M., "Spreading Resistance: A Comparison of Sampling Volume Correction Factors in High Resolution Quantitative Spreading Resistance," *Emerging Semiconductor Technology, ASTM STP 960*, D. C., Gupta and P. H., Langer, eds., ASTM, 1987, pp. 502–520.

(**5**) Ehrstein, J. R., *Spreading Resistance Symposium, op. cit.* , p. 249.

(**6**) Vieweg-Gutberlet, F. G., *Semiconductor Silicon, 1977* , Proceedings of the Third International Symposium on Silicon Materials Science and Technology, H. R. Huff and E. Sertle, eds., The Electrochemical Society, Princeton, NJ, May 1977, p. 387.

(**7**) Mayer, A., and Shwartzman, S., *Spreading Resistance Symposium, op. cit.*, pp. 123–136.

(**8**) Tong, A. H., Gorey, E. F., and Schneider, C. P.," Apparatus for the Measurement of Small Angles," *Review of Scientific Instruments*, Vol 43, February 1972, p. 320.

(**9**) Deines, J. L., Gorey, E. F., Michel, A. E., and Poponiak, M. R., *Spreading Resistance Symposium, op. cit.* , pp. 169–178.

(**10**) Albers, J., "Comparison of Spreading Resistance Correction Factor Algorithms Using Model Data," *Solid State Electronics*, Vol 23, 1980, pp. 1197–1205.

(**11**) Thurber, W. R., et al, *Semiconductor Measurement Technology: The Relationship Between Resistivity and Dopant Density for Phosphorus- and Boron-Doped Silicon*, NBS Special Publication 400–64, April 1981.

TABLE 1 Depth Resolution for Probe Step Increments of 5 and 10 µm as Related to Bevel Angle (and Sine) and Bevel Length

Depth Resolution, µm		Angle Θ	Sin Θ	Bevel Length Needed for Complete Profile, mm		
10-µm Probe Step Increment	5-µm Probe Step Increment			2-µm Layer	10-µm Layer	50-µm Layer
0.05	0.025	16′	0.005	0.4	2.0	10.0
0.1	0.05	34′	0.01	0.2	1.0	5.0
0.2	0.1	1°9′	0.02	0.1	0.5	2.5
0.5	0.25	2°52′	0.05	0.04	0.2	1.0
1.0	0.5	5°43′	0.01	0.02	0.1	0.5
2.0	1.0	11°33′	0.20	0.01	0.05	0.25

TABLE A1.1 Range of Measurement Conditions in Round Robin

Parameter	Range of Values Among Data Taken
Bevel angle tangent for emitter/base	0.00198 to 0.022
Step size used for emitter/base (µm)	1.0 to 10
Number data points for emitter	19 to 112
Number data points for base	12 to 83
Bevel angle tangent for collector/buried layer	0.006 to 0.54
Step size used for collector/buried layer (µm)	2.5 to 10
Probe separation (µm)	5 to 55
Probe load (g)	1.5 to 10

TABLE A1.2 Summary of Average Values and Relative Precision (RIS) for Two Laboratory Groups on Bipolar Transistor Test Specimen

Laboratory Group		Structure Locations			Structure Values						
		Emitter-Base Junction [A]	Base-Collector Junction [A]	Buried Layer-Substrate Junction [A]	Emitter Minimum Resistivity [B]	Emitter Sheet Resistance [C]	Base Minimum Resistivity [B]	Base Sheet Resistance [C]	Collector Average Resistivity [B]	Buried Layer Minimum Resistivity [B]	Substrate Resistivity [B]
5 Laboratories Same Multilayer Algorithm	Average value	0.632	1.078	8.25	0.000834	25.2	0.110	4357	0.899	0.00398	15.1
	(RIS), %	4.0	3.5	2.1	21	22	16	23	23	14	21
4 Laboratories Different Analysis Algorithms	Average value	0.608	1.033	8.14	0.00127	29.6	0.214	7823	0.882	0.0048	14.4 [D]
	(RIS), %	3.4	4.1	3.3	13	15	28	21	20	16	[D]

[A] All junction depths are measured in micrometres.
[B] All resistivity is measured in ohm centimetres.
[C] All sheet resistance is measured in ohms.
[D] Two laboratories did not provide data.

TABLE X2.1 Model Spreading Resistance Data for Two-Peak Implant into Same-Type Substrate—Based on Current Distribution for a Thick, Uniform Slab

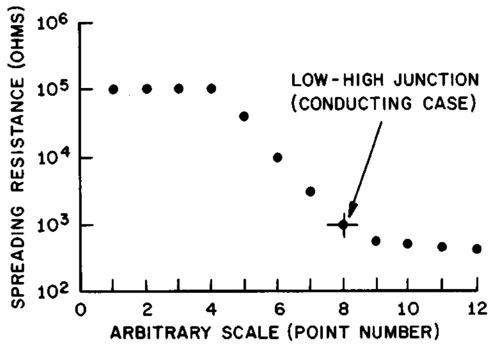
Depth,μ m	Resistivity, Ω·cm	Log (Spreading Resistance)	Depth, μm	Resistivity, Ω·cm	Log (Spreading Resistance)
0.000	125.369000	4.23926E 00	1.140	0.022750	2.90454E 00
0.030	120.144000	4.08949E 00	1.170	0.021180	2.94894E 00
0.060	97.905400	3.86737E 00	1.200	0.020490	3.00251E 00
0.090	51.546400	3.52198E 00	1.230	0.020630	3.06599E 00
0.120	16.909000	3.07652E 00	1.260	0.021600	3.13992E 00
0.150	4.752590	2.69239E 00	1.290	0.023490	3.22476E 00
0.180	1.418380	2.47106E 00	1.320	0.026490	3.32087E 00
0.210	0.490040	2.37538E 00	1.350	0.030930	3.42869E 00
0.240	0.203960	2.33733E 00	1.380	0.037310	3.54876E 00
0.270	0.102250	2.32157E 00	1.410	0.046520	3.68207E 00
0.300	0.059210	2.31532E 00	1.440	0.060160	3.83001E 00
0.330	0.037490	2.31448E 00	1.470	0.081310	3.99419E 00
0.360	0.025020	2.31800E 00	1.500	0.116320	4.17858E 00
0.390	0.017420	2.32608E 00	1.530	0.178830	4.37448E 00
0.420	0.012740	2.33965E 00	1.560	0.299610	4.58588E 00
0.450	0.009914	2.35997E 00	1.590	0.551050	4.80077E 00
0.480	0.008296	2.38822E 00	1.620	1.111160	5.00504E 00
0.510	0.007523	2.42495E 00	1.650	2.432660	5.18185E 00
0.540	0.007423	2.46974E 00	1.680	5.679230	5.31597E 00
0.570	0.007974	2.52059E 00	1.710	13.670400	5.40203E 00
0.600	0.009299	2.57413E 00	1.740	31.670200	5.44888E 00
0.630	0.011690	2.62606E 00	1.770	62.636700	5.47159E 00
0.660	0.015700	2.67252E 00	1.800	95.352400	5.48166E 00
0.690	0.022230	2.71077E 00	1.830	115.136000	5.48558E 00
0.720	0.032850	2.74000E 00	1.860	123.022000	5.48688E 00
0.750	0.050810	2.76077E 00	1.890	125.519000	5.48726E 00
0.780	0.083880	2.77417E 00	1.920	126.219000	5.48736E 00
0.810	0.147680	2.78110E 00	1.950	126.400000	5.48739E 00
0.840	0.228320	2.78215E 00	1.980	126.444000	5.48740E 00
0.870	0.216900	2.77876E 00	2.010	126.454000	5.48740E 00
0.900	0.150370	2.77570E 00	2.040	126.456000	5.48740E 00
0.930	0.102200	2.77606E 00	2.070	126.456000	5.48740E 00
0.960	0.073100	2.78017E 00	2.100	126.456000	5.48740E 00
0.990	0.054970	2.78812E 00	2.130	126.456000	5.48740E 00
1.020	0.043060	2.80027E 00	2.160	126.456000	5.48740E 00
1.050	0.034920	2.81718E 00	2.190	126.456000	5.48740E 00
1.080	0.029260	2.83959E 00	2.220	126.456000	5.48740E 00
1.110	0.025350	2.86840E 00			

TABLE X2.2 Model Spreading Resistance Data for Thin Epitaxial Layer on Conducting Substrate—Based on Current Distribution for a Thick, Uniform Slab

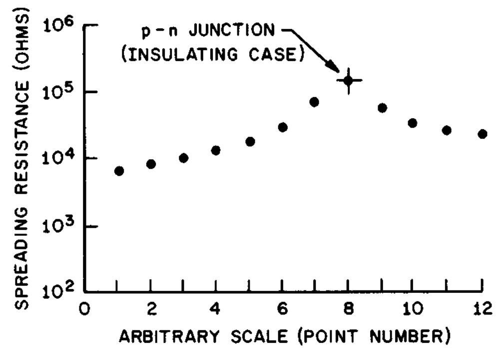
Depth (μm)	Resistivity (Ω·cm)	Log (Spreading Resistance)
0.000	10.000000	4.0266E 00
0.025	10.000000	4.0194E 00
0.050	10.000000	4.0119E 00
0.075	10.000000	4.0041E 00
0.100	10.000000	3.9960E 00
0.125	10.000000	3.9877E 00
0.150	10.000000	3.9790E 00
0.175	10.000000	3.9700E 00
0.200	10.000000	3.9606E 00
0.225	10.000000	3.9509E 00
0.250	10.000000	3.9407E 00
0.275	10.000000	3.9302E 00
0.300	10.000000	3.9191E 00
0.325	10.000000	3.9076E 00
0.350	10.000000	3.8956E 00
0.375	10.000000	3.8830E 00
0.400	10.000000	3.8698E 00
0.425	10.000000	3.8560E 00
0.450	10.000000	3.8415E 00
0.475	10.000000	3.8262E 00
0.500	10.000000	3.8101E 00
0.525	10.000000	3.7930E 00
0.550	10.000000	3.7750E 00
0.575	10.000000	3.7559E 00
0.600	10.000000	3.7355E 00
0.625	10.000000	3.7138E 00
0.650	10.000000	3.6905E 00
0.675	10.000000	3.6655E 00
0.700	10.000000	3.6385E 00
0.725	10.000000	3.6092E 00
0.750	10.000000	3.5772E 00
0.775	10.000000	3.5420E 00
0.800	10.000000	3.5030E 00
0.825	10.000000	3.4593E 00
0.850	10.000000	3.4098E 00
0.875	10.000000	3.3528E 00
0.900	10.000000	3.2859E 00
0.925	10.000000	3.2051E 00
0.950	10.000000	3.1039E 00
0.975	10.000000	2.9693E 00
1.000	10.000000	2.7701E 00
1.025	2.659150	2.3865E 00
1.050	0.707110	2.1810E 00
1.075	0.188030	2.1053E 00
1.100	0.050000	2.0844E 00
1.125	0.050000	2.0844E 00
1.150	0.050000	2.0844E 00
1.175	0.050000	2.0844E 00
1.200	0.050000	2.0844E 00
1.225	0.050000	2.0844E 00

TABLE X2.3 Model Spreading Resistance Data for a Thin Epitaxial Layer on a Conducting Substrate—Based on Uniform Density Current Distribution Through the Probes

Depth (μm)	Resistivity (Ω·cm)	Log (Spreading Resistance)
0.000	10.000000	4.0832E 00
0.025	10.000000	4.0761E 00
0.050	10.000000	4.0687E 00
0.075	10.000000	4.0611E 00
0.100	10.000000	4.0532E 00
0.125	10.000000	4.0449E 00
0.150	10.000000	4.0364E 00
0.175	10.000000	4.0275E 00
0.200	10.000000	4.0182E 00
0.225	10.000000	4.0086E 00
0.250	10.000000	3.9985E 00
0.275	10.000000	3.9880E 00
0.300	10.000000	3.9770E 00
0.325	10.000000	3.9655E 00
0.350	10.000000	3.9535E 00
0.375	10.000000	3.9409E 00
0.400	10.000000	3.9277E 00
0.425	10.000000	3.9138E 00
0.450	10.000000	3.8991E 00
0.475	10.000000	3.8837E 00
0.500	10.000000	3.8674E 00
0.525	10.000000	3.8502E 00
0.550	10.000000	3.8319E 00
0.575	10.000000	3.8125E 00
0.600	10.000000	3.7918E 00
0.625	10.000000	3.7697E 00
0.650	10.000000	3.7461E 00
0.675	10.000000	3.7206E 00
0.700	10.000000	3.6930E 00
0.725	10.000000	3.6631E 00
0.750	10.000000	3.6305E 00
0.775	10.000000	3.5946E 00
0.800	10.000000	3.5548E 00
0.825	10.000000	3.5103E 00
0.850	10.000000	3.4599E 00
0.875	10.000000	3.4020E 00
0.900	10.000000	3.3340E 00
0.925	10.000000	3.2523E 00
0.950	10.000000	3.1501E 00
0.975	10.000000	3.0145E 00
1.000	10.000000	2.8141E 00
1.025	2.659150	2.4273E 00
1.050	0.707110	2.2186E 00
1.075	0.188030	2.1413E 00
1.100	0.050000	2.1198E 00
1.125	0.050000	2.1198E 00
1.150	0.050000	2.1198E 00
1.175	0.050000	2.1198E 00
1.200	0.050000	2.1198E 00
1.225	0.050000	2.1198E 00

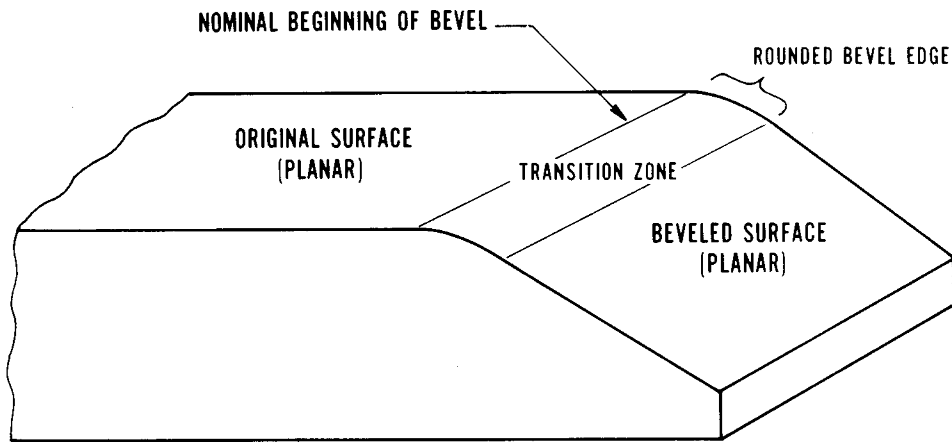


(*a*) Conducting Boundary



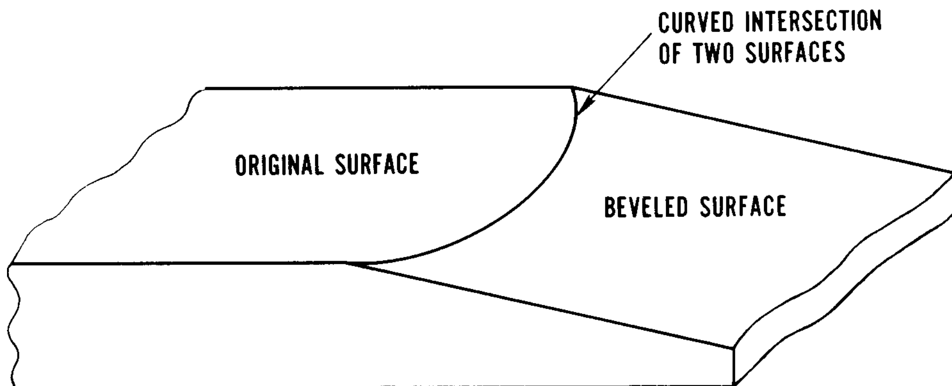
(*b*) Insulating Boundary

FIG. 1 Identification of Boundaries from a Spreading Resistance Profile



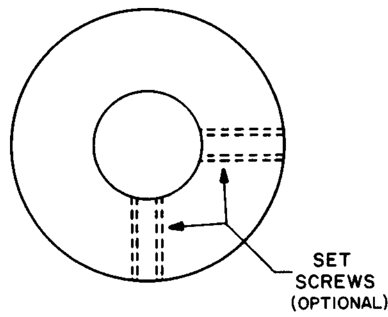
NOTE 1—Instead of a sharp intersection between two surfaces, a transition region exists which makes it impossible to determine the beginning of the beveled surface. In the transition region the depth being probed is not a linear function of the probe step increment.

FIG. 2 Sketch Illustrating One Form of Defective Beveling: Bevel Edge Rounding



NOTE 1—Instead of a straight line intersection between the original and beveled surfaces, an arc-shaped intersection exists indicating that one, or both surfaces are non-planar. In the presence of this defect any means for determining the bevel angle which samples a finite width of the specimen along the arc will not provide a unique angle value.

FIG. 3 Sketch Illustrating One Form of Defective Beveling: Bevel Edge Arcing



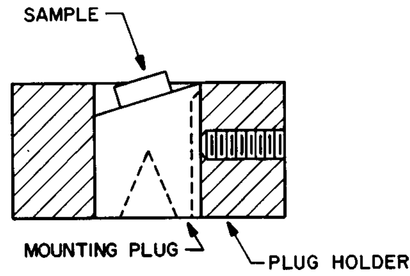


FIG. 4 Typical Plug (Beveling Block) and Holder Used for Beveling

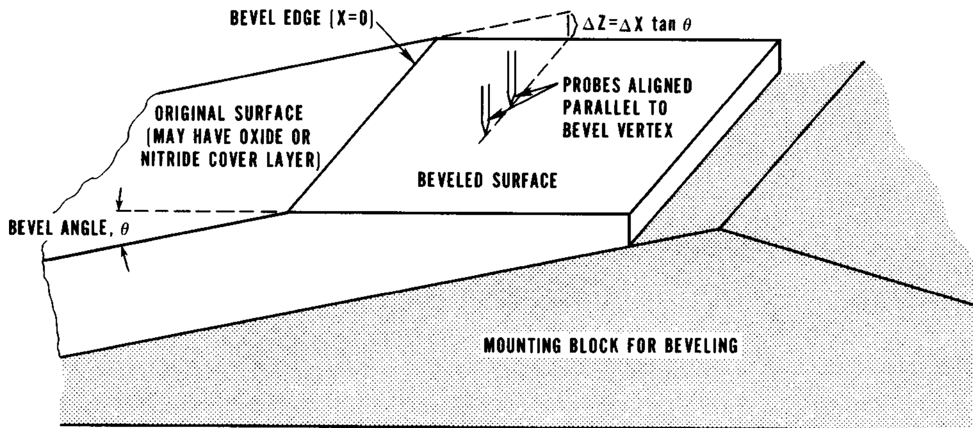


FIG. 5 Sketch of Beveled Silicon Wafer on Mounting Block Showing Ideal Beveling: Two Planar Surfaces Intersecting Along a Straight Line with No Transition Region Between the Planar Surfaces; Also Showing (Two) Probes Aligned Parallel to Bevel Edge

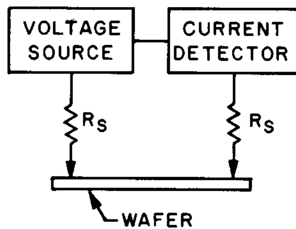
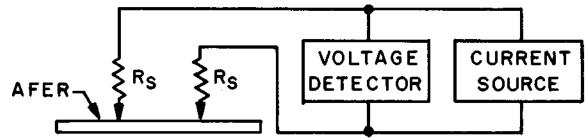
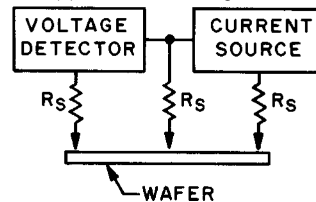


FIG. 6 Electrical Circuit for the Constant-Voltage Method, Usable Only With the Two-Probe Arrangement



(*a*) Two-Probe Arrangement



(*b*) Three-Probe Arrangement

FIG. 7 Electrical Circuit for the Constant-Current Method

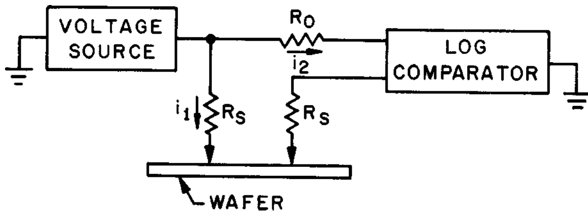
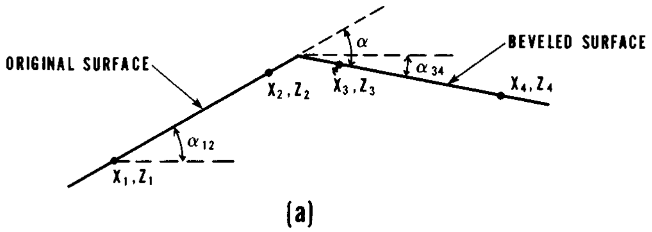
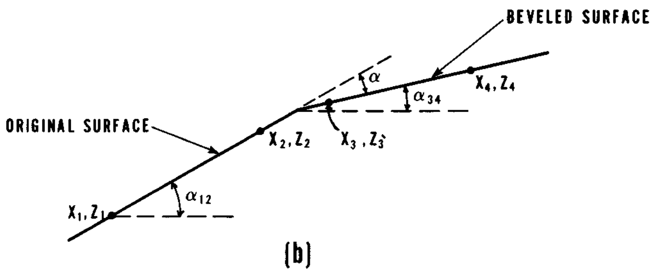


FIG. 8 Electrical Circuit for the Current Comparator Method Usable Only for the Two-Probe Arrangement





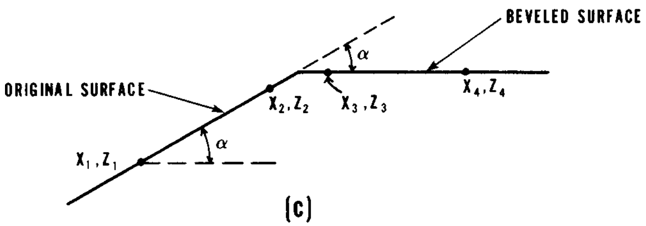


FIG. X1.1 Schematic Representation of Lateral Measurement Locations and Corresponding Vertical Microscope Positions for Three Cases of Specimen Mounting on Microscope Stage

The American Society for Testing and Materials takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, 100 Barr Harbor Drive, West Conshohocken, PA 19428.