



National Institute of Standards & Technology

Certificate

Standard Reference Material[®] 2543

Silicon Resistivity Standard - 1 ohm·cm Level

Certification Batch #2

Serial No.:

This Standard Reference Material (SRM) is intended primarily for use in the determination of sheet resistance and bulk resistivity using the DC four-point probe method [1,2]. SRM 2543 is a nominal 100 mm diameter Czochralski-grown, boron-doped silicon wafer with (100) crystallographic orientation. The wafer has a nominal thickness of 0.625 mm.

Wafer preparation was performed utilizing a simultaneous two-sided lapping process with a nominal 12 μm aluminum oxide abrasive. This wafer unit was individually measured. The certified sheet resistance and resistivity values at the wafer's center are given in Table 1a and the sheet resistance is given at 60° increments on the radii of 5 mm and 10 mm circles in Table 1b. The stated uncertainty values for this unit are derived from a statistical analysis of the entire lot of wafers produced at the 1 ohm·cm resistivity level. A summary of these uncertainties is given in Table 2.

Previous silicon resistivity SRMs have also been used as de facto standards for calibration of noncontact (eddy current) instruments and/or with other material systems such as compound semiconductors. This SRM has similar utility, but it must be emphasized that NIST has rigorously investigated only the DC four-point method on bulk silicon. This SRM cannot be used as a thickness reference standard.

Expiration of Certification: The certification of this SRM is deemed to be indefinite in duration, provided the SRM is handled and stored in accordance with the "Care and Handling" and "Cautions to User" sections of this certificate. However, the certification will be nullified if the SRM is damaged, contaminated, or modified. It is possible to take several thousand individual probe measurements before performance degradation occurs. Any degradation due to probe damage is evidenced by a shift in measured resistivity and a significant increase in measurement standard deviation. When such a change in measurement results, which cannot be traced to the electronics or to a deteriorated probe, occurs, the certification is invalidated and the SRM should no longer be used.

The doped bulk silicon material was supplied by Recticon¹ Corp., Pottstown, PA.

The coordination and overall direction of this SRM were provided by J.R. Ehrstein of the NIST Semiconductor Electronics Division. Resistivity measurements for this SRM were performed by D.R. Ricks of the NIST Semiconductor Electronics Division.

Statistical guidance and analysis were provided by H-k. Liu of the NIST Statistical Engineering Division.

The support aspects involved in the issuance of this SRM were coordinated through the NIST Standard Reference Materials Program by B.S. MacDonald of the NIST Measurement Services Division.

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Certificate Issue Date: 15 June 2004

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¹Certain commercial equipment, instruments, or materials are identified in this certificate in order to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Table 1a. Certified Values and Expanded Uncertainties at Center of SRM 2543

Serial No.:

Sheet Resistance ^a (Center) (Corrected to 23 °C)	Resistivity (Corrected to 23 °C)
ohms \pm 0.004 34 ohms	ohm·cm \pm 0.0027 ohm·cm

Table 1b. Certified Values and Expanded Uncertainties on the 5 mm and 10 mm Radius Measurement Circles of SRM 2543

Sheet Resistance ^a (Corrected to 23 °C)		
Angle	5 mm Radius	10 mm Radius
0° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms
60° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms
120° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms
180° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms
240° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms
300° \pm 3°	ohms \pm 0.046 ohms	ohms \pm 0.046 ohms

^a Values for sheet resistance may be converted to resistivity values by multiplying by the wafer thickness.

Certified Value Uncertainties: The uncertainties for the certified values were calculated in accordance with the ISO and NIST Guides [3]. The sources of uncertainty are identified in Table 2, with a more detailed explanation given in reference 4. It is assumed that rectangular distributions underlie all Type B uncertainty determinations; for a rectangular distribution, the variance is one-third of the half-width. The combined uncertainty is obtained from the square-root of the sum of the Type A and Type B variances. The expanded uncertainty is obtained by multiplying this combined uncertainty by a coverage factor; following NIST guidelines, a coverage factor of two is used, and the expanded uncertainty is written as a 2 σ value. There are 25 800 degrees of freedom for the uncertainty of center averages and 21 500 degrees of freedom for the uncertainty of individual measurements.

The following components of uncertainty were determined by Type A evaluations: 1) electrical measurement process precision (short term) was estimated from a pooling of the wafer center measurement variances of the 104 wafers in this batch with corresponding variances from pre- and post-certification control experiments; 2) day-to-day and longer term process variabilities were obtained from comparison of pre- and post-certification control experiment values and from check wafer data taken during the course of the certification; 3) the effect of using a single four-point probe, out of all possible probes, for certification was estimated from the control experiments which utilized multiple probes; 4) dependence, upon ambient illumination level, of the resistivity value measured for this SRM was estimated from additional measurements - in the dark, and in illumination sufficiently bright (krypton bulb) to reach saturation. The combined variance from the above sources applies both to sheet resistance and to resistivity values. An additional term for the typical variation of thickness values for individual wafer units is included in the uncertainty for resistivity values, but not in that for sheet resistance. (Note: The electrical measurement process variance contributes only one-sixth as much to the uncertainty of the average of 6 measurements as it does to the uncertainty of the individual measurements.)

Type B determinations were made for the following sources of uncertainty that affect both the resistivity and the sheet resistance values: 1) digital voltmeter and standard resistor calibration uncertainty; 2) uncertainty in the measurement of wafer temperature that affects correction of the measured values from ambient temperature to 23 °C. An additional source evaluated by Type B determination that affects only the resistivity value is the uncertainty due to transfer of the thickness scale from gauge blocks through the thickness tool to the wafer.

Other possible sources of uncertainty were considered but were estimated to be negligible based on experience. Detailed descriptions of the certification procedure, measurement process control, and uncertainty analysis are contained in reference 4.

Table 2. Summary of Uncertainty for Individual Measurement Values

	Sheet Resistance	Resistivity
Total Type A Uncertainty	0.022 29 ohms	0.001 39 ohm·cm
Total Type B Uncertainty	0.006 29 ohms	0.000 429 ohm·cm
Combined Uncertainty (1 σ)	0.023 16 ohms	0.001 454 ohm·cm
Expanded Uncertainty (2 σ)	0.046 32 ohms	0.002 908 ohm·cm

Measurement Procedure: Each unit was individually measured by using a single in-line probe with nominal 1.59 mm probe point separation and meeting the specifications of ASTM F84 [1] for bulk silicon. The dual-configuration method [2,5] of four-point probe measurements was used, with configuration “A” being identical to that in ASTM F84. Eighteen measurements were taken on each wafer: six were taken at the wafer center, separated by rotations of approximately 30° (these are averaged and reported for the center as a single location); six were taken at sites separated by rotations of 60° around a circle of radius 5 mm (0.2 in); and six were taken at sites around a circle of radius 10 mm (0.4 in), again with rotational separations of 60°. The measurements described by these two circles started on the positive X-axis (negative Y-axis is normal to the wafer flat) and proceeded counterclockwise. Due to the nature of resistivity variations in silicon, the values certified for these circles cannot be used to predict the resistivity in other regions of the wafer.

A DC current value was selected to give a measured specimen voltage between 9.95 mV and 10.05 mV in configuration “A” for the first measurement at the wafer center. This current setting was maintained on the current supply for all subsequent measurements. Values of current at each of the measurement sites were determined to five or more digits using a standard resistor.

Thickness uniformity for the region of the electrical measurements was evaluated for each wafer by using the nine-site plan of ASTM Method F84, with a radius of approximately 19 mm for the locations of the corners of this pattern. All points were required to have a thickness within 1 μ m of the value at the center of the wafer to be acceptable for use as an SRM. The average of all nine thickness measurements for this wafer is given in Table 3 and should be used to convert from sheet resistance to resistivity for each of the electrical measurement sites.

Table 3. Measurement Conditions for Certification

Date of Certification Measurements:	_____
Average Wafer Thickness:	_____ μm \pm _____ μm
Nominal Measurement Current:	2.8 mA
Temperature of Heat Sink While Measuring at:	
First Measurement Site:	_____ $^{\circ}\text{C}$
Last Measurement Site:	_____ $^{\circ}\text{C}$
Temperature Coefficient of Resistivity, C_T (first site) [1]:	_____ $\%/^{\circ}\text{C}$
Relative Humidity:	< 50 % RH
Correction Terms Used:	
1) Average factor to convert the voltage-to-current (V/I) ratio to sheet resistance, for configuration "A" at the wafer center:	_____
2) Correction factor related to ratio of wafer thickness to probe separation for calculating wafer sheet resistance:	_____
3) Correction for temperature to 23 $^{\circ}\text{C}$ (first site):	_____

INSTRUCTIONS FOR USE

Notes on SRM Use: A four-point probe with spacing equal to or greater than twice the wafer thickness effectively averages sheet resistance from front to back surfaces of a wafer. For this reason, either surface of the SRM wafer may be measured by the user's four-point probe with negligible expected differences in the values measured.

When the user needs to convert sheet resistance values measured on this SRM to resistivity values, NIST recommends using the thickness value given in this Certificate to obtain best agreement with the certified resistivity value. Due to the lapped surface texture of this wafer, independent thickness measurements by the user are likely to result in a slightly different value from that reported here, particularly if a different type of thickness gauge is used. This would result in a degraded transfer of resistivity scale using this SRM although it would have no bearing on the transfer of the sheet resistance value. Due to its lapped surface texture, **this wafer cannot be used as a reference material for wafer thickness.**

Care and Handling: The lapped surfaces of this SRM give it a general robustness and improved measurement stability. Nevertheless, reasonable care in handling, such as the use of gloves, finger cots, vacuum paddles, or tweezers should be exercised to maintain wafer cleanliness. Storage in any reasonable, noncorrosive, nontoxic environment, in conjunction with the packaging provided, should prove adequate for maintaining stability of the SRM. Cleaning with the proper surfactant or with isopropyl alcohol, together with thorough rinsing in deionized water and thorough drying, has been found acceptable for removing most surface stains. The use of hydrofluoric acid or elevated temperature treatments is discouraged. The SRM should not be stored or measured in an ambient relative humidity above 50 %.

Cautions to User: NIST strongly recommends that this SRM not be used alone for calibration or for testing the linearity or other performance characteristic of sheet resistance/resistivity measuring equipment. For any of these applications, use one or more of the other wafers in the SRM series 2541 through 2547 in addition to this SRM.

NIST recommends that the user generate secondary standards based on this SRM rather than employ it for routine use [6]. This is particularly important for users of four-point probe instruments which may gradually damage silicon wafers with repeated probing.

Because of a *photosensitivity* of the boron-doped Czochralski wafers used for this SRM, the user is strongly encouraged to read NIST Special Publication 260-131, pages 36-38, and Appendix 7, sections 3 and 4 [4] for a general discussion of the photosensitivity, its impact, and the evaluation of its magnitude for the wafers used for this SRM.

This SRM may not be appropriate for calibrating sheet resistance measurement instruments or for evaluating the sheet resistance/resistivity of materials other than silicon due to differences of material and instrument parameters relative to single crystal silicon wafers and to DC conduction measurements. Among the material parameters are conduction and carrier scattering mechanisms, grain boundary effects on conduction, and the relative importance of sample surface vs bulk in responding to the measurement stimulus. Instrument parameters include electromagnetic frequency of the measurement stimulus, the associated skin depth in the materials being measured, and sampling volume of the instrumentation in relation to material grain size. Parties interested in extending the calibration use of these SRMs are advised to contact Dr. James R. Ehrstein of the NIST Semiconductor Electronics Division at (301) 975-2060.

Silicon has a noticeable temperature dependence for resistivity. Accurate values of the temperature coefficient of silicon resistivity are available for the range 18 °C to 28 °C [1]. If the user makes measurements at a temperature other than 23 °C, the resulting resistivity and sheet resistance values must be corrected to 23 °C for best agreement with the certified values. Corrections for measurements made outside of the 18 °C to 28 °C range may suffer from reduced accuracy.

The localized variations in resistivity typically found in silicon wafers such as those of this SRM may limit the user's ability to obtain exactly the certified values if instrumentation is employed having a sampling volume different from that of a 1.59 mm four-point probe. However, it is likely that imprecision of the user's instrumentation will be a more important limitation to transfer of the certified value than differences in sampling volume.

REFERENCES

- [1] ASTM Method F84-93; *Standard Test Method for Measuring Resistivity of Silicon Wafers With an In-Line Four-Point Probe*; Annu. Book of ASTM Stand., Vol. 10.05 (1999).
- [2] ASTM Method F1529-96; *Standard Test Method for Sheet Resistance Uniformity Evaluation by In-line Four-Point Probe with the Dual-Configuration Procedure*; Annu. Book of ASTM Stand., Vol. 10.05 (2002).
- [3] ISO; *Guide to the Expression of Uncertainty in Measurement*; ISBN 92-67-10188-9, 1st ed.; International Organization for Standardization: Geneva, Switzerland (1993); see also Taylor, B.N.; Kuyatt, C.E.; *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*; NIST Technical Note 1297; U.S. Government Printing Office: Washington, DC (1994); available at <http://physics.nist.gov/Pubs/>.
- [4] Ehrstein, J.R.; Croarkin, M.C.; *Standard Reference Materials: The Certification of 100 mm Diameter Silicon Resistivity SRMs 2541 through 2547 Using Dual-Configuration Four-Point Probe Measurements*; Natl. Inst. Stand. Technol., Spec. Publ. 260-131 (1997).
- [5] Perloff, D.S.; Gan, J.N.; Wahl, F.E.; *Dose Accuracy and Doping Uniformity of Ion Implantation Equipment*; Solid State Technology; Vol. 24, No. 2, pp. 112-120 (1981).
- [6] ASTM Guide F1527-94; *Standard Guide for Application of Standard Reference Materials and Reference Wafers for Calibration and Control of Instruments for Measuring Resistivity of Silicon*; Annu. Book of ASTM Stand., Vol. 10.05 (2000).

Users of this SRM should ensure that the certificate in their possession is current. This can be accomplished by contacting the SRM Program at: telephone (301) 975-6776; fax (301) 926-4751; e-mail srminfo@nist.gov; or via the Internet at <http://www.nist.gov/srm>.

APPENDIX

The SRM 2541 through SRM 2547 series is intended to replace the previously issued silicon resistivity sets, SRM 1521 through SRM 1523, and offer several comparative advantages: 1) larger size for better equipment compatibility; 2) better uniformity of both thickness and resistivity; 3) reduced measurement uncertainty due to an improved certification procedure; and 4) additional measurement sites for better characterization of resistivity uniformity.

Stability Tests: Silicon wafers from all previous resistivity SRMs have been monitored by NIST for as long as 15 years with no cumulative drift of the measured resistivity values. While there were some measurement values in that monitoring sequence that were outside the confidence limits determined from the certification uncertainty, those outlier values are believed to have been due to long-term measurement environment variability as well as to the use of single-configuration probe measurements, which are more sensitive to changes of probes or to probe tip condition than are the dual-configuration measurements used for current SRM certification.

Tests of the stability of silicon resistivity reference materials with repeated probing have shown that it is possible to make several thousand probe measurements without significant changes of value, even when the probing is confined to a very localized area. **However, the use of excessively sharp or damaged probes, or of unconditioned new probes, may accelerate the accumulation of crystalline damage** that leads to a shift in resistivity values or degraded measurement repeatability. This is particularly true for float zone or NTD silicon, both of which have low oxygen content and are more susceptible to crystalline damage from mechanical contact.

Multilaboratory Measurement Reproducibility: Test results of multilaboratory comparisons of four-probe resistivity measurements are useful for guidance on confidence intervals that might be expected when using this SRM to transfer resistivity scale values between NIST and the user's laboratory. While there have not been any reported multilaboratory tests using the dual-configuration method of measurement, a number of tests have been conducted by ASTM using the single-configuration methodology (ASTM F84). These tests yielded a multilaboratory precision of just under 0.7 % for wafers with resistivities up to 120 $\text{ohm}\cdot\text{cm}$, and just under 1.7 % for wafers between 120 $\text{ohm}\cdot\text{cm}$ and 500 $\text{ohm}\cdot\text{cm}$. These values lead to 99 % confidence intervals of ± 2 % for wafers up to 120 $\text{ohm}\cdot\text{cm}$ and ± 5 % for wafers between 120 $\text{ohm}\cdot\text{cm}$ and 500 $\text{ohm}\cdot\text{cm}$ [1]. Because of the relatively nonuniform, small (5 cm) diameter wafers used for those ASTM multilaboratory tests, the resulting confidence intervals are believed to be quite conservative compared to what could be expected on wafers with improved uniformity such as those from this SRM series, particularly if the dual-configuration four-point probe methodology were employed by all laboratories.

Equipment¹ Used for Wafer Qualification and for SRM Certification:

For the Determination of Thickness:

Random wafers - large area thickness uniformity prescreening:	ADE Model 6033T [®]
All wafers - certified thickness, 9 sites:	Haidenhain Certo 60 [®]
Gauge blocks for calibration of Certo 60:	Webber Croblox [®] 0.609 65 mm
	Webber Croblox 0.625 00 mm
	Webber Croblox 0.660 45 mm

For Electrical Measurements:

Current Supply:	Electronic Development Corporation Model #CR 103
Standard Resistor:	1 ohm, Leeds & Northrup, NBS Type #1593079
DVM:	Hewlett-Packard Model #3456
Probe:	Kulicke & Soffa Fell Probe #283

REFERENCE

- [1] Bullis, W.M.; *Standard Measurements of the Resistivity of Silicon by the Four-Probe Method*; NBSIR 74-496, p. 75; Nat. Bur. Std., U.S. Department of Commerce: (1974).

¹Certain commercial materials and equipment are identified in order to adequately specify the experimental procedure. Such identification does not imply a recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for this purpose.