Optical, Thermoradiative, Thermophysical, and Mechanical Properties of Silicon

Ronald H. Bogaard and David L. Taylor

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Optical, Thermoradiative, Thermophysical, and Mechanical Properties of Silicon

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**Supplementary Notes**
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**Abstract**
This report presents numerical data and technical information on the properties of pure silicon and doped silicon materials. Materials comprise a variety of doped silicon materials, having both n-type and p-type conduction. Property coverage includes optical (absorption coefficient and refractive index), thermoradiative (normal spectral reflectance, angular spectral reflectance, normal spectral emittance, and normal spectral transmittance), thermophysical (thermal conductivity, specific heat, thermal expansion, and lattice parameter), and mechanical (elastic constants, stress-strain, yield strength under tensile, compressive, and shear loading, flexural strength, and fracture toughness).

Property data are compiled from scientific and technical literature. The compiled data are scrutinized and evaluated through an established set of selection criteria for semiconductor and infrared window materials, and are analyzed for effects due to composition (purity, dopants, carrier concentration), temperature, and wavelength.

The electronic version of this report as a computerized PC-based database is also available on a diskette for use on personal computers. This electronic version is for efficient data retrieval, manipulation, and application.

**Subject Terms**
Silicon, dopant effects, n-type, p-type, optical properties, thermophysical properties, mechanical properties

**Classification**
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HIGH TEMPERATURE MATERIALS INFORMATION ANALYSIS CENTER
(HTMIAC)

Operated by
CENTER FOR INFORMATION AND NUMERICAL DATA ANALYSIS AND SYNTHESIS
(CINDAS)
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906-1398
PREFACE

"Optical, Thermoradiative, Thermophysical, and Mechanical Properties of Silicon" is being prepared by the High Temperature Materials Information Analysis Center (HTMIAC). It is published at this time as an interim report so as to make the evaluated information available early to users in the DoD and DoD-contractor community and to avoid significant delays. The interim report will be improved and expanded and the data contained herein will be further analyzed with the aim of republishing it in final format as an authoritative databook.

Property data for silicon that are available in the literature are widely recognized to be sensitive to variations in material related factors. Many issues that are important in determining property behavior of these materials have been brought forward and widely discussed in the literature. Our objective is to bring them together into a single volume and to document the data and supporting information that bear upon the behavior of silicon, in particular the temperature, wavelength, and composition dependence of its properties.

The present compilation of analyzed property data on silicon is part of a continuing effort for the development, expansion, update, and upgrade of the High Temperature Materials Properties (HTMP) Database, a computerized numerical/technical database containing numerical data and technical information on materials and properties of interest to high temperature materials technologies. The property data compiled are extensively searched from the worldwide scientific and technical literature, subjected to selection criteria established for material property data capture activities at HTMIAC/CINDAS, and evaluated and analyzed on a property basis in order to clarify discordant data issues and to make effects of affecting variables upon property behavior more readily evident to users of the data.

This interim report is organized with major sections according to property groups. Coverage within each property group is incorporated into subsections dealing with the individual properties of the same property group. Each subsection consists of a sequence of individual data sets and accompanying data plot figures for a series of silicon materials including: intrinsic, various dopants, n-type, and p-type. The property sequence listed under each of the property groups is as follows: for optical properties: absorption coefficient and refractive index; for thermoradiative properties: normal spectral reflectance, angular spectral reflectance, normal spectral emittance, and normal spectral transmittance; for thermophysical properties: thermal conductivity, specific heat, thermal expansion, and lattice parameter; and for mechanical properties: elastic constant, stress-strain, yield strength under tensile, compressive, and shear loading, flexural strength, and fracture toughness.
HTMIAC, a DoD Information Analysis Center, is sponsored and administratively managed and funded by the Defense Technical Information Center (DTIC), ATTN: DTIC-AI, Cameron Station, Alexandria, VA 22304-6145, and is under the IACs program management of Dr. Forrest R. Frank. HTMIAC is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana 47906-1398 under Contract DLA900-93-D-5002. The contract was awarded to Purdue by the Defense Electronics Supply Center (DESC), ATTN: DESC-EACC, Dayton, Ohio 45444-5181 with Ms. Cheryl A. Montoney as the Contracting Officer. HTMIAC is under the technical direction and monitoring of the Contracting Officer’s Technical Representative (COTR), Mr. Jerome Persh, Senior Specialist for Materials and Structures, Office of the Director of Defense Research and Engineering (Advanced Technology), ATTN: ODDR&E (AT), The Pentagon, Room 3D1089, Washington, DC 20301-3080 and the Technical Coordinator, Mr. Roger E. Rondeau, Air Force Wright Laboratory, ATTN: WL/MLPJ, Wright-Patterson Air Force Base, Ohio 45433-7702.

HTMIAC serves as the DoD’s central source of engineering data and technical information on high temperature materials, especially in the critical technology areas of aerospace structural composites and metals, infrared detector materials, and coatings, and the effects of laser irradiation on these materials. It supports the DoD research, development, test, evaluation, engineering, and acquisition programs as well as defense systems and military hardware in general where scientific and technical information (STI) on high temperature materials technologies is required, and supports the laser effects technology communities with laser-materials interaction data as well as high temperature material property data for laser structural and detector susceptibility, vulnerability, survivability, and hardening assessments and studies in particular. Furthermore, HTMIAC supports the Joint Logistics Commanders/ Joint Directors of Laboratories Technology Panel for Advanced Materials (TPAM), and provides assistance to or receives guidance from other Defense programs and groups as designated by the COTR.

This report is credited to the collective efforts of many HTMIAC and/or CINDAS staff members, who contributed to the technical work and/or the preparation of this report. In addition to the authors listed on the cover, P. D. Desai, J. F. Chaney, V. Ramdas, H. H. Li, J. C. F. Chen, and Carol Dwenger also contributed to this report.

C. Y. Ho
Director
HTMIAC and CINDAS
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2.5. Mechanical Properties
MATERIAL: Silicon: P doped

PROPERTY: Elastic Constant, C(11)

Composition
2.0e19 cm⁻³ Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Specimens prepared from LopeX-grade silicon.

Specimen Identification
Dimensions (Geometry):
Length 1.5 cm
Width 1.5 cm
Thickness 1.5 cm

Additional Properties
Density Initial/Final (295K):
2.3297 g cm⁻³

Additional Properties
Carrier/Impurity Conc.:
Dislocation Density 500. cm⁻²
Temperature 298. K
Electrical Properties:
Electrical Resistivity 3.26e-05 Ω m
Temperature 298. K
Other Properties-Textual:
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
Velocity of Sound Method
Sound velocities determined by a pulse-echo technique.
Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X: Temperature K
Y: Elastic Constant, C(11) Pa

Data Points:

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2.000e+01  1.639e+11
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8.000e+01  1.642e+11
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1.200e+02  1.644e+11
1.400e+02  1.644e+11
1.600e+02  1.644e+11
1.800e+02  1.644e+11
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2.400e+02  1.643e+11
2.600e+02  1.642e+11
2.800e+02  1.641e+11
3.000e+02  1.640e+11
3.200e+02  1.638e+11

Comments on Data
Data read from figure. Uncertainty is within +/- 1.0 pct.

Reference
ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.
Hall, J. J.
PHYS. REV.
Figure 97 Elastic Constant, C(11) of Silicon: P doped
Material Preparation
Crystal Growing Method:
Specimens prepared from Lopex-grade silicon.

Specimen Identification
Dimensions (Geometry):
<table>
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Additional Properties
Density Initial/Final (295K):
2.3290 g cm⁻³

Additional Properties
Carrier/Impurity Conc. :
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<td>500. cm⁻²</td>
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Electrical Properties :
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<td>150. 10⁻³ Ω cm</td>
<td>298. K</td>
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Other Properties-Textual :
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
Velocity of Sound Method
Sound velocities determined by a pulse-echo technique.
Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X : Temperature
Y : Elastic Constant, C(11)

Data Points:
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1.800e+02  1.669e+11
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2.600e+02  1.661e+11
2.800e+02  1.659e+11
3.000e+02  1.656e+11
3.200e+02  1.654e+11

Comments on Data
Data read from figure. Uncertainty is within +/- 1.0 pct.

Reference
ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.
Hall, J. J.
PHYS. REV.
Figure 98. Elastic Constant, $C(11)$ of Silicon, n-type
MATERIAL: Silicon, p-type

PROPERTY: Elastic Constant, C(11)

Composition
99.993 weight percent Silicon
10 ppm atomic Aluminum
<2 ppm atomic Boron
<3 ppm atomic Chromium
20 ppm atomic Copper
25 ppm atomic Iron
<3 ppm atomic Magnesium
3 ppm atomic Manganese
<3 ppm atomic Nickel
<0.5 ppm atomic Silver

Specimen Identification
Dimensions (Geometry):
Length 25.0 mm
Diameter 25.0 mm

Additional Properties
Density Initial/Final (295K):
2.329 g cm\(^{-3}\)

Additional Properties
Electrical Properties:
Electrical Resistivity 0.22 \(\Omega\) cm
Temperature 298. K
Hole Concentration 4.8e16 cm\(^{-3}\)
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Pulse-Echo Sound Velocity Technique
Elastic constants calculated from the measured velocities through the single crystal.
Parameters-Textual:
Frequency was 30 MHz with 1.5 kHz band

Measured/Evaluated Properties
X: Temperature K
Y: Elastic Constant, C(11) Pa

Data Points:

336
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<td>2.980e+02</td>
<td>1.652e+11</td>
</tr>
<tr>
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<td>1.650e+11</td>
</tr>
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<td>7.880e+02</td>
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<tr>
<td>1.103e+03</td>
<td>1.539e+11</td>
</tr>
</tbody>
</table>

**Comments on Data**
Uncertainty in RT C11 value is +/- 1.32, data calculated from Table III.

**Reference**
USE OF THE IMPULSE METHOD FOR MEASURING THE ELASTIC CONSTANTS OF SOLIDS AT HIGH TEMPERATURES. APPLICATION TO SINGLE-CRYSTAL SILICON.
Ezz-El-Arab, M. A.
ANN. PHYS. (PARIS)
7 (3), 133-58, 1972.
Figure 99 Elastic Constant, $C(11)$ of Silicon, p-type
Specimen Identification
Dimensions (Geometry):
- Length: 20. mm
- Thickness: 4. mm
- Width: 4. mm

Additional Properties
Density Initial/Final (295K):
- Initial: 2.33 g cm⁻³

Additional Properties
Electrical Properties:
- Electrical Resistivity: 420. Ω cm
- Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
- Resonance-Frequency Sound Velocity Technique
- Resonance frequencies ranged from 127 to 280 kHz.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
- Pressure: 1.e-04 mmHg

Measured/Evaluated Properties
X: Temperature K
Y: Elastic Constant, C(11) Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>1.660e+11</td>
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<td>2.930e+02</td>
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<tr>
<td>4.730e+02</td>
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<td>5.730e+02</td>
<td>1.573e+11</td>
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<td>6.730e+02</td>
<td>1.557e+11</td>
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<td>1.542e+11</td>
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<td>1.527e+11</td>
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<tr>
<td>9.730e+02</td>
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</tbody>
</table>
1.073e+03  1.496e+11
1.173e+03  1.475e+11
1.273e+03  1.451e+11
1.690e+03  1.339e+11

**Comments on Data**
Values at 0. and 1690. K were extrapolated.
Uncertainty is within +/- 0.4 pct. Data read from table.
The natural frequencies were used to determine the Young’s
moduli and the elasticity moduli as a function of temperature
were calculated using published thermal expansion values.

**Reference**
TEMPERATURE DEPENDENCE OF ELASTIC CONSTANTS OF
SILICON.
Burenkov, Yu. A. Nikanorov, S. P.
FIZ. TVERD. TELA ( LENINGRAD )
16 ( 5 ), 1496-8, 1974.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
16 ( 5 ), 963-4, 1974 )
Figure 100  Elastic Constant, C(11) of Silicon, p-type
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(11)

Specimen Identification
Dimensions (Geometry):
  Length  2.0  cm
  Width  1.3  cm

Additional Properties
Density Initial/Final (295K):
  2.331  g cm^{-3}

Measurement/Evaluation Method
Name/Description:
  Single Transducer Sound Velocity Method
  Elastic constants calculated from the measured velocities of propagation through the single crystal.

Measured/Evaluated Properties
X: Temperature  K
Y: Elastic Constant, C(11)  Pa

Data Points:

\[
\begin{array}{cc}
X & Y \\
7.300e+01 & 1.675e+11 \\
9.000e+01 & 1.674e+11 \\
1.000e+02 & 1.674e+11 \\
1.200e+02 & 1.673e+11 \\
1.400e+02 & 1.672e+11 \\
1.600e+02 & 1.670e+11 \\
1.800e+02 & 1.669e+11 \\
2.000e+02 & 1.667e+11 \\
2.400e+02 & 1.663e+11 \\
2.600e+02 & 1.661e+11 \\
2.800e+02 & 1.659e+11 \\
3.000e+02 & 1.656e+11 \\
3.100e+02 & 1.655e+11 \\
\end{array}
\]

Comments on Data
smoothed data.

Reference
MEASUREMENT OF ELASTIC CONSTANTS AT LOW TEMPERATURES
BY MEANS OF ULTRASONIC WAVES - DATA FOR SILICON AND GERMANIUM SINGLE CRYSTALS, AND FOR FUSED SILICA.
McSkimin, H. J.
J. APPL. PHYS.
24 (8), 988-97, 1953.
Figure 101 Elastic Constant, C(11) of Silicon
Composition
2.0e19 cm\(^{-3}\) Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Specimens prepared from Lopex-grade silicon.

Specimen Identification
Dimensions (Geometry):
- Length: 1.5 cm
- Width: 1.5 cm
- Thickness: 1.5 cm

Additional Properties
Density Initial/Final (295K):
2.3297 g cm\(^{-3}\)

Additional Properties
Carrier/Impurity Conc.:
- Dislocation Density: 500. cm\(^{-2}\)
- Temperature: 298. K

Electrical Properties:
- Electrical Resistivity: 3.26e-05 Ω m
- Temperature: 298. K

Other Properties-Textual:
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
- Velocity of Sound Method
- Sound velocities determined by a pulse-echo technique.
- Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(12) Pa

Data Points:

\[
\begin{align*}
X & : 4.000e+00 \\
Y & : 6.694e+10 \\
\text{Remarks:} & : \text{smoothed data}
\end{align*}
\]
2.000e+01  6.691e+10
4.000e+01  6.683e+10
6.000e+01  6.672e+10
8.000e+01  6.658e+10
1.000e+02  6.643e+10
1.200e+02  6.625e+10
1.400e+02  6.606e+10
1.600e+02  6.586e+10
1.800e+02  6.567e+10
2.000e+02  6.547e+10
2.200e+02  6.529e+10
2.400e+02  6.512e+10
2.600e+02  6.497e+10
2.800e+02  6.484e+10
3.000e+02  6.475e+10
3.200e+02  6.469e+10

Comments on Data
Data read from figure. Uncertainty is within +/- 1.0 pct.

Reference
ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.
Hall, J. J.
PHYS. REV.
Figure 102 Elastic Constant, C(12) of Silicon: P doped
MATERIAL: Silicon, n-type

PROPERTY: Elastic Constant, C(12)

Material Preparation
Crystal Growing Method:
Specimens prepared from Lopex-grade silicon.

Specimen Identification
Dimensions (Geometry):
Length 1.5 cm
Width 1.5 cm
Thickness 1.5 cm

Additional Properties
Density Initial/Final (295K):
2.3290 g cm^{-3}

Additional Properties
Carrier/Impurity Conc.:
Dislocation Density 500. cm^{-2}
Temperature 298. K

Electrical Properties:
Electrical Resistivity 150. \times 10^{-3} \Omega cm
Temperature 298. K

Other Properties-Textual:
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
Velocity of Sound Method
Sound velocities determined by a pulse-echo technique.
Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(12) Pa

Data Points:

<table>
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<th>Remarks:</th>
</tr>
</thead>
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<tr>
<td>2.000e+01</td>
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</tr>
<tr>
<td>4.000e+01</td>
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<td>6.000e+01</td>
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</tr>
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</table>
8.000e+01  6.485e+10  
1.000e+02  6.479e+10  
1.200e+02  6.472e+10  
1.400e+02  6.465e+10  
1.600e+02  6.458e+10  
1.800e+02  6.450e+10  
2.000e+02  6.441e+10  
2.200e+02  6.432e+10  
2.400e+02  6.422e+10  
2.600e+02  6.411e+10  
2.800e+02  6.400e+10  
3.000e+02  6.388e+10  
3.200e+02  6.376e+10  

**Comments on Data**  
Data read from figure. Uncertainty is within +/- 1.0 pct.

**Reference**  
**ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.**  
Hall, J. J.  
*PHYS. REV.*  
Figure 103 Elastic Constant, C(12) of Silicon, n-type
**MATERIAL:** Silicon, p-type

**PROPERTY:** Elastic Constant, C(12)

**Composition**

<table>
<thead>
<tr>
<th>Composition</th>
<th>weight percent</th>
<th>Silicon</th>
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<td>10 ppm atomic</td>
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<td>&lt;2</td>
<td>ppm atomic</td>
<td>Boron</td>
</tr>
<tr>
<td>&lt;3</td>
<td>ppm atomic</td>
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<td>20</td>
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<td>ppm atomic</td>
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<td>ppm atomic</td>
<td>Manganese</td>
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<td>ppm atomic</td>
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<tr>
<td>&lt;0.5</td>
<td>ppm atomic</td>
<td>Silver</td>
</tr>
</tbody>
</table>

**Specimen Identification**

Dimensions (Geometry):

- Length: 25.0 mm
- Diameter: 25.0 mm

**Additional Properties**

Density Initial/Final (295K):

- 2.329 g cm$^{-3}$

**Additional Properties**

Electrical Properties:

- Electrical Resistivity: 0.22 Ω cm
- Temperature: 298. K
- Hole Concentration: 4.8e16 cm$^{-3}$
- Temperature: 298. K

**Measurement/Evaluation Method**

Name/Description:

- Pulse-Echo Sound Velocity Technique
- Elastic constants calculated from the measured velocities through the single crystal.

Parameters-Textual:

- Frequency was 30 MHz with 1.5 kHz band

**Measured/Evaluated Properties**

- X: Temperature K
- Y: Elastic Constant, C(12) Pa

Data Points:
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.980e+02</td>
<td>6.390e+10</td>
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<tr>
<td>3.230e+02</td>
<td>6.380e+10</td>
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<td>3.680e+02</td>
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<td>6.300e+10</td>
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<td>1.103e+03</td>
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</tbody>
</table>

Comments on Data
Uncertainty in RT C12 value is +/- 1.74, data calculated from Table III.

Reference
USE OF THE IMPULSE METHOD FOR MEASURING THE ELASTIC CONSTANTS OF SOLIDS AT HIGH TEMPERATURES.
APPLICATION TO SINGLE-CRYSTAL SILICON.
Ezz-El-Arab, M. A.
ANN. PHYS. ( PARIS )
7 (3), 133-58, 1972.
Figure 104 Elastic Constant, C(12) of Silicon, p-type
MATERIAL: Silicon, p-type

PROPERTY: Elastic Constant, C(12)

Specimen Identification
Dimensions (Geometry):
Length 20. mm
Thickness 4. mm
Width 4. mm

Additional Properties
Density Initial/Final (295K):
2.33 g cm$^{-3}$

Additional Properties
Electrical Properties:
Electrical Resistivity 420. Ω cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Resonance-Frequency Sound Velocity Technique
Resonance frequencies ranged from 127 to 280 kHz.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
Pressure 1.e-04 mmHg

Measured/Evaluated Properties
X : Temperature
Y : Elastic Constant, C(12)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>6.020e+10</td>
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<tr>
<td>2.930e+02</td>
<td>5.780e+10</td>
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<tr>
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<td>4.730e+02</td>
<td>5.770e+10</td>
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<tr>
<td>9.730e+02</td>
<td>5.480e+10</td>
</tr>
</tbody>
</table>
1.073e+03  5.390e+10  
1.173e+03  5.280e+10  
1.273e+03  5.150e+10  
1.690e+03  4.590e+10

**Comments on Data**
Data at 0. and 1690. k were extrapolated.
Uncertainty is within +/- 0.4 pct. Data read from table.
The natural frequencies were used to determine the Young's
moduli and the elasticity moduli as a function of temperature
were calculated using published thermal expansion values.

**Reference**
TEMPERATURE DEPENDENCE OF ELASTIC CONSTANTS OF
SILICON.
Burenkov, Yu. A.  Nikanorov, S. P.
FIZ. TVERD. TELA ( LENINGRAD )
16 ( 5 ), 1496-8, 1974.
(FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
16 ( 5 ), 963-4, 1974 )
Figure 105 Elastic Constant, C(12) of Silicon, p-type
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(12)

Specimen Identification
Dimensions (Geometry):
  Length : 2.0 cm
  Width  : 1.3 cm

Additional Properties
Density Initial/Final (295K):
  2.331 g cm\(^{-3}\)

Measurement/Evaluation Method
Name/Description:
  Single Transducer Sound Velocity Method
  Elastic constants calculated from the measured velocities of
  propagation through the single crystal.

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(12) Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.300e+01</td>
<td>6.498e+10</td>
</tr>
<tr>
<td>9.000e+01</td>
<td>6.494e+10</td>
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<td>1.200e+02</td>
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<td>1.400e+02</td>
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<td>6.388e+10</td>
</tr>
<tr>
<td>3.100e+02</td>
<td>6.382e+10</td>
</tr>
</tbody>
</table>

Comments on Data
smoothed data.

Reference
MEASUREMENT OF ELASTIC CONSTANTS AT LOW TEMPERATURES
BY MEANS OF ULTRASONIC WAVES - DATA FOR SILICON AND
GERMANIUM SINGLE CRYSTALS, AND FOR FUSED SILICA.
McSkimin, H. J.
J. APPL. PHYS.
24 (8), 988-97, 1953.
Figure 106 Elastic Constant, C(12) of Silicon
Composition
2.0e19 cm\(^{-3}\) Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Specimens prepared from Loprox-grade silicon.

Specimen Identification
Dimensions (Geometry):
Length 1.5 cm
Width 1.5 cm
Thickness 1.5 cm

Additional Properties
Density Initial/Final (295K):
2.3297 g cm\(^{-3}\)

Additional Properties
Carrier/Impurity Conc.:
Dislocation Density 500. cm\(^{-2}\)
Temperature 298. K
Electrical Properties:
Electrical Resistivity 3.26e-05 Ω m
Temperature 298. K
Other Properties-Textual:
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
Velocity of Sound Method
Sound velocities determined by a pulse-echo technique.
Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(44) Pa

Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks} \\
4.000e+00 & 7.999e+10 & \text{smoothed data} \\
\end{array}
\]
2.000e+01  7.999e+10
4.000e+01  7.999e+10
6.000e+01  7.997e+10
8.000e+01  7.995e+10
1.000e+02  7.992e+10
1.200e+02  7.988e+10
1.400e+02  7.983e+10
1.600e+02  7.977e+10
1.800e+02  7.971e+10
2.000e+02  7.964e+10
2.200e+02  7.956e+10
2.400e+02  7.948e+10
2.600e+02  7.939e+10
2.800e+02  7.930e+10
3.000e+02  7.920e+10
3.200e+02  7.910e+10

Comments on Data
Data read from figure. Uncertainty is within +/- 1.0 pct.

Reference
ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.
Hall, J. J.
PHYS. REV.
Figure 107 Elastic Constant, C(44) of Silicon: P doped
Material Preparation
Crystal Growing Method:
Specimens prepared from Lopex-grade silicon.

Specimen Identification
Dimensions (Geometry):
Length 1.5 cm
Width 1.5 cm
Thickness 1.5 cm

Additional Properties
Density Initial/Final (295K):
2.3290 g cm$^{-3}$

Additional Properties
Carrier/Impurity Conc.:
Dislocation Density 500. cm$^{-2}$
Temperature 298. K

Electrical Properties:
Electrical Resistivity 150. $10^{-3}$ Ω cm
Temperature 298. K

Other Properties-Textual:
Carrier density was from Hall effect measurement.

Measurement/Evaluation Method
Name/Description:
Velocity of Sound Method
Sound velocities determined by a pulse-echo technique.
Radio frequency pulses of 12., 36., or 60. MHz were used.

Measured/Evaluated Properties
X: Temperature K
Y: Elastic Constant, C(44) Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.000e+00</td>
<td>8.016e+10</td>
<td>smoothed data</td>
</tr>
<tr>
<td>2.000e+01</td>
<td>8.019e+10</td>
<td></td>
</tr>
<tr>
<td>4.000e+01</td>
<td>8.022e+10</td>
<td></td>
</tr>
<tr>
<td>6.000e+01</td>
<td>8.022e+10</td>
<td></td>
</tr>
</tbody>
</table>
8.000e+01  8.022e+10
1.000e+02  8.020e+10
1.200e+02  8.017e+10
1.400e+02  8.012e+10
1.600e+02  8.007e+10
1.800e+02  8.001e+10
2.000e+02  7.994e+10
2.200e+02  7.986e+10
2.400e+02  7.978e+10
2.600e+02  7.970e+10
2.800e+02  7.961e+10
3.000e+02  7.952e+10
3.200e+02  7.943e+10

**Comments on Data**
Data read from figure. Uncertainty is within +/- 1.0 pct.

**Reference**
ELECTRONIC EFFECTS IN THE ELASTIC CONSTANTS OF n-TYPE SILICON.
Hall, J. J.
PHYS. REV.
Figure 108 Elastic Constant, C(44) of Silicon, n-type
MATERIAL: Silicon, p-type

PROPERTY: Elastic Constant, C(44)

Composition

<table>
<thead>
<tr>
<th>Weight Percent</th>
<th>composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.993</td>
<td>weight percent</td>
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<td>ppm atomic</td>
</tr>
<tr>
<td>3</td>
<td>ppm atomic</td>
</tr>
<tr>
<td>&lt;3</td>
<td>ppm atomic</td>
</tr>
<tr>
<td>&lt;0.5</td>
<td>ppm atomic</td>
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</tbody>
</table>

Specimen Identification

Dimensions (Geometry):

<table>
<thead>
<tr>
<th>Length</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Additional Properties

Density Initial/Final (295K):

2.329 \( g \text{ cm}^{-3} \)

Additional Properties

Electrical Properties:

<table>
<thead>
<tr>
<th>Electrical Resistivity</th>
<th>Temperature</th>
<th>Hole Concentration</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22 ( \Omega \text{ cm} )</td>
<td>298. ( \text{K} )</td>
<td>4.8e16 ( \text{cm}^{-3} )</td>
<td>298. ( \text{K} )</td>
</tr>
</tbody>
</table>

Measurement/Evaluation Method

Name/Description:

Pulse-Echo Sound Velocity Technique

Elastic constants calculated from the measured velocities through the single crystal.

Parameters-Textual:

Frequency was 30 MHz with 1.5 kHz band

Measured/Evaluated Properties

<table>
<thead>
<tr>
<th>X</th>
<th>Temperature</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Elastic Constant, C(44)</td>
<td>Pa</td>
</tr>
</tbody>
</table>

Data Points:
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.980e+02</td>
<td>7.900e+10</td>
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<tr>
<td>3.230e+02</td>
<td>7.890e+10</td>
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<tr>
<td>3.480e+02</td>
<td>7.880e+10</td>
</tr>
<tr>
<td>3.680e+02</td>
<td>7.870e+10</td>
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<tr>
<td>3.980e+02</td>
<td>7.850e+10</td>
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<tr>
<td>4.230e+02</td>
<td>7.840e+10</td>
</tr>
<tr>
<td>4.480e+02</td>
<td>7.830e+10</td>
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<tr>
<td>4.730e+02</td>
<td>7.810e+10</td>
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<td>4.980e+02</td>
<td>7.800e+10</td>
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<td>5.330e+02</td>
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<td>5.730e+02</td>
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<td>6.130e+02</td>
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<td>6.530e+02</td>
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<td>6.980e+02</td>
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<td>7.280e+02</td>
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<td>7.580e+02</td>
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<td>7.880e+02</td>
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<td>8.180e+02</td>
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<td>8.530e+02</td>
<td>7.580e+10</td>
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<td>9.030e+02</td>
<td>7.550e+10</td>
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<tr>
<td>9.530e+02</td>
<td>7.510e+10</td>
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<td>7.440e+10</td>
</tr>
<tr>
<td>1.103e+03</td>
<td>7.410e+10</td>
</tr>
</tbody>
</table>

**Comments on Data**
Uncertainty in RT C44 value is +/- 0.32, data calculated from Table III.

**Reference**
USE OF THE IMPULSE METHOD FOR MEASURING THE ELASTIC CONSTANTS OF SOLIDS AT HIGH TEMPERATURES.
APPLICATION TO SINGLE-CRYSTAL SILICON.
Ezz-El-Arab, M. A.
ANN. PHYS. (PARIS)
7 (3), 133-58, 1972.
Figure 109 Elastic Constant, C(44) of Silicon, p-type
MATERIAL: Silicon, p-type

PROPERTY: Elastic Constant, C(44)

Specimen Identification
Dimensions (Geometry):
- Length: 20. mm
- Thickness: 4. mm
- Width: 4. mm

Additional Properties
Density Initial/Final (295K):
- 2.33 g cm\(^{-3}\)

Additional Properties
Electrical Properties:
- Electrical Resistivity: 420. \(\Omega\) cm
- Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
- Resonance-Frequency Sound Velocity Technique
- Resonance frequencies ranged from 135 to 280 kHz.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
- Pressure: 1.e-04 mmHg

Measured/Evaluated Properties
X: Temperature
Y: Elastic Constant, C(44)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>8.200e+10</td>
</tr>
<tr>
<td>2.930e+02</td>
<td>8.000e+10</td>
</tr>
<tr>
<td>3.730e+02</td>
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<td>4.730e+02</td>
<td>7.900e+10</td>
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<tr>
<td>5.730e+02</td>
<td>7.840e+10</td>
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<td>6.730e+02</td>
<td>7.780e+10</td>
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<td>7.730e+02</td>
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<td>8.730e+02</td>
<td>7.660e+10</td>
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<tr>
<td>9.730e+02</td>
<td>7.590e+10</td>
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</tbody>
</table>
1.073e+03    7.520e+10
1.173e+03    7.450e+10
1.273e+03    7.370e+10
1.690e+03    7.040e+10

Comments on Data
Data at 0. and 1690. k were extrapolated.
Uncertainty is within +/- 0.4 pct. Data read from table.
The natural frequencies were used to determine the Young’s
moduli and the elasticity moduli as a function of temperature
were calculated using published thermal expansion values.

Reference
TEMPERATURE DEPENDENCE OF ELASTIC CONSTANTS OF
SILICON.
Burenkov, Yu. A.  Nikanorov, S. P.
FIZ. TVERD. TELA ( LENINGRAD )
16 ( 5 ), 1496-8, 1974.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
16 ( 5 ), 963-4, 1974 )
Figure 110  Elastic Constant, C(44) of Silicon, p-type
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(44)

Specimen Identification
Dimensions (Geometry):
  Length  2.0 cm
  Width  1.3 cm

Additional Properties
Density Initial/Final (295K):
  2.331 g cm⁻³

Measurement/Evaluation Method
Name/Description:
  Single Transducer Sound Velocity Method
  Elastic constants calculated from the measured velocities of
  propagation through the single crystal.

Measured/Evaluated Properties
X : Temperature  K
Y : Elastic Constant, C(44)  Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.300e+01</td>
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<tr>
<td>1.600e+02</td>
<td>7.997e+10</td>
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<td>1.800e+02</td>
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<td>7.954e+10</td>
</tr>
<tr>
<td>3.100e+02</td>
<td>7.951e+10</td>
</tr>
</tbody>
</table>

Comments on Data
smoothed data.

Reference
MEASUREMENT OF ELASTIC CONSTANTS AT LOW TEMPERATURES
BY MEANS OF ULTRASONIC WAVES - DATA FOR SILICON AND
GERMANIUM SINGLE CRYSTALS, AND FOR FUSED SILICA.
McSkimin, H. J.
J. APPL. PHYS.
24 (8), 988-97, 1953.
Figure 111 Elastic Constant, C(44) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(111)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length: 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Parameters-Textual:
Hard and or elastic constants by harmonic generation.
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.
Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X: Temperature
Y: Elastic Constant, C(111)

K

Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.000e+00</td>
<td>-8.800e+11</td>
<td>St. dev.=+/-16 GPa</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>-8.490e+11</td>
<td>St. dev.=+/-14 GPa</td>
</tr>
<tr>
<td>2.980e+02</td>
<td>-8.340e+11</td>
<td>St. dev.=+/-11 GPa</td>
</tr>
</tbody>
</table>

Comments on Data
Data taken from table.
Agreement with theory is good.
Reference
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300
AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 112 Elastic Constant, $C(111)$ of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(111)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.539 cm
Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100], [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Parameters-Textual:
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.
Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X: Temperature
Y: Elastic Constant, C(111)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-8.750e+11</td>
</tr>
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<td>9.000e+00</td>
<td>-8.810e+11</td>
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<td>2.400e+01</td>
<td>-8.680e+11</td>
</tr>
<tr>
<td>4.200e+01</td>
<td>-8.810e+11</td>
</tr>
<tr>
<td>6.000e+01</td>
<td>-8.550e+11</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>-8.550e+11</td>
</tr>
</tbody>
</table>
9.900e+01  -8.420e+11  
1.180e+02  -8.550e+11  
1.310e+02  -8.480e+11  
1.480e+02  -8.480e+11  
1.680e+02  -8.480e+11  
2.000e+02  -8.470e+11  
2.250e+02  -8.530e+11  
2.420e+02  -8.470e+11  
2.610e+02  -8.460e+11  
2.720e+02  -8.460e+11  
2.990e+02  -8.330e+11

Comments on Data
Data read from figure 3.

Reference
THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND 300 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
54 (2), 752-7, 1983.
Figure 113 Elastic Constant, $C_{(111)}$ of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(112)

Descriptive Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning:
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification:
Dimensions (Geometry):
Length: 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method:
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties:
X : Temperature
Y : Elastic Constant, C(112)

K
Pa

Data Points:

| X         | Y         | Remarks:
|-----------|-----------|----------------
| 4.000e+00 | -5.150e+11| St. dev.=+/-26 GPa |
| 7.700e+01 | -5.240e+11| St. dev.=+/-31 GPa |
| 2.980e+02 | -5.310e+11| St. Dev.=+/-32 GPa |

Comments on Data:
Data taken from table.
Agreement with theory is good.

Reference:
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300 AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 114 Elastic Constant, $C(112)$ of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(112)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.539 cm

Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100] [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(112) Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.000e+00</td>
<td>-4.310e+10</td>
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<tr>
<td>1.000e+01</td>
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<td>-4.620e+10</td>
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<tr>
<td>2.400e+01</td>
<td>-4.680e+10</td>
</tr>
<tr>
<td>4.500e+01</td>
<td>-4.810e+10</td>
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<tr>
<td>6.100e+01</td>
<td>-4.990e+10</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>-5.050e+10</td>
</tr>
</tbody>
</table>
1.010e+02  -5.050e+10
1.170e+02  -5.050e+10
1.310e+02  -4.980e+10
1.490e+02  -5.100e+10
1.690e+02  -5.100e+10
1.990e+02  -5.030e+10
2.240e+02  -5.030e+10
2.430e+02  -5.090e+10
2.630e+02  -5.090e+10
2.730e+02  -5.090e+10
2.980e+02  -5.020e+10

Comments on Data
Data read from figure 3.

Reference
THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND 300 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
54 (2), 752-7, 1983.
Figure 115 Elastic Constant, C(112) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(123)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X : Temperature
Y : Elastic Constant, C(123)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.000e+00</td>
<td>2.700e+10</td>
<td>St. dev.=+/-24 GPa</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>-8.000e+09</td>
<td>St. dev.=+/-20 GPa</td>
</tr>
<tr>
<td>2.980e+02</td>
<td>-2.000e+09</td>
<td>St. dev.=+/-18 GPa</td>
</tr>
</tbody>
</table>

Comments on Data
Data taken from table.
Agreement with theory is good.

Reference
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300 AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 116 Elastic Constant, C(123) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(123)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.539 cm

Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100] [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique

Parameters-Textual:
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X: Temperature  K
Y: Elastic Constant, C(123)  Pa

Data Points:

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<tr>
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<th>Y</th>
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</thead>
<tbody>
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<td>-1.530e+10</td>
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<tr>
<td>2.200e+01</td>
<td>-3.490e+10</td>
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<td>-5.320e+10</td>
</tr>
<tr>
<td>3.900e+01</td>
<td>-8.470e+10</td>
</tr>
</tbody>
</table>
4.700e+01  -9.910e+10  
5.800e+01  -1.265e+11  
6.800e+01  -1.567e+11  
8.100e+01  -1.593e+11  
1.220e+02  -1.658e+11  
1.350e+02  -1.697e+11  
1.500e+02  -1.631e+11  
1.710e+02  -1.762e+11  
2.000e+02  -1.853e+11  
2.240e+02  -1.839e+11  
2.430e+02  -1.891e+11  
2.610e+02  -1.891e+11  
2.730e+02  -1.917e+11  
3.000e+02  -1.891e+11  

**Comments on Data**

Data read from figure.
Shows maximum sensitivity to temperature.

**Reference**

THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND 300 DEGREE K.

Philip, J. Breazeale, M. A.

J. APPL. PHYS.

54 (2), 752-7, 1983.
Figure 117. Elastic Constant, C(123) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(144)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(144) Pa

Data Points:

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<tr>
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<td>St. dev.=+/-8 GPa</td>
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<td>2.980e+02</td>
<td>-9.500e+10</td>
<td>St. dev.=+/-24 GPa</td>
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Comments on Data
Data taken from table.
Agreement with theory is good.

Reference
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300 AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 118 Elastic Constant, $C(144)$ of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(144)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.539 cm

Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100] [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X : Temperature
Y : Elastic Constant, C(144)

Data Points:

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<td>2.700e+09</td>
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<tr>
<td>5.100e+01</td>
<td>-3.100e+09</td>
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</tbody>
</table>
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7.700e+01  -5.500e+09
1.000e+02  -1.020e+10
1.170e+02  -1.030e+10
1.310e+02  -1.040e+10
1.470e+02  -1.160e+10
1.680e+02  -1.400e+10
1.980e+02  -1.640e+10
2.240e+02  -1.900e+10
2.420e+02  -2.010e+10
2.630e+02  -2.020e+10
2.740e+02  -2.140e+10
3.010e+02  -2.270e+10

Comments on Data
Data read from figure 4.
Shows maximum sensitivity to temperature.

Reference
THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND 300 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
54 (2), 752-7, 1983.
Figure 119  Elastic Constant, $C_{144}$ of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(166)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length: 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X: Temperature
Y: Elastic Constant, C(166)

Data Points:

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<td>-2.960e+11</td>
<td>St. dev. = +/- 12 GPa</td>
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</table>

Comments on Data
Data taken from table.
Agreement with theory is good.

Reference
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300
AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 120 Elastic Constant, C(166) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(166)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.539 cm

Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100], [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.

Parameters-Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X: Temperature K
Y: Elastic Constant, C(166) Pa

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<td>-3.240e+10</td>
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<td>9.900e+01</td>
<td>-3.240e+10</td>
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1.180e+02 -3.230e+10
1.320e+02 -3.230e+10
1.490e+02 -3.230e+10
1.690e+02 -3.160e+10
1.990e+02 -3.160e+10
2.230e+02 -3.160e+10
2.410e+02 -3.150e+10
2.600e+02 -3.090e+10
2.720e+02 -3.090e+10
2.970e+02 -3.080e+10
\end{verbatim}

\textbf{Comments on Data}
Data read from figure 3.

\textbf{Reference}
THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN
PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND
300 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
54 (2), 752-7, 1983.
Figure 121 Elastic Constant, C(166) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(456)

Descriptors - Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length 2.5214 cm

Additional Identifiers:
Length is average of 2.5171, 2.5222, and 2.5248 cm along [100], [110], and [111] orientations, respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of finite amplitude longitudinal ultrasonic wave.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine nonlinearity parameters.

Parameters - Codified:
Frequency: 30 MHz

Measured/Evaluated Properties
X : Temperature K
Y : Elastic Constant, C(456) Pa

Data Points:

<table>
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<tr>
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<th>Remarks:</th>
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<td>4.000e+00</td>
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<td>St. dev.=+/-11 GPa</td>
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<td>7.700e+01</td>
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<td>St. dev.=+/-34 GPa</td>
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<td>2.980e+02</td>
<td>-7.400e+09</td>
<td>St. dev.=+/-22 GPa</td>
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</table>

Comments on Data
Data taken from table.
Agreement with theory is good.

Reference
TEMPERATURE VARIATION OF SOME COMBINATIONS OF
THIRD-ORDER ELASTIC CONSTANTS OF SILICON BETWEEN 300 AND 3 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
52 (5), 3383-7, 1981.
Figure 122 Elastic Constant, C(456) of Silicon
MATERIAL: Silicon

PROPERTY: Elastic Constant, C(456)

Descriptors-Textual:
After surface treatment, ends were covered with 0.1 microns of copper to make them conductive.

Additional Preparation/Conditioning
Surface Treatment:
Sample ends are lapped and polished until optically flat and parallel to within 15 inches of arc.

Specimen Identification
Dimensions (Geometry):
Length: 2.539 cm

Additional Identifiers:
Length is average of 2.571, 2.522, and 2.5248 cm in [100] [110], and [111] orientations respectively.

Measurement/Evaluation Method
Name/Description:
Ultrasonic Harmonic Generation Technique
Excitation of a finite amplitude longitudinal ultrasonic wave which propagates along the principal crystallographic direction.
Measurement of fundamental amplitude and the generated second harmonic amplitude used to determine the nonlinearity parameter which contain three linear combinations of 3rd order elastic constants.

Parameters-Codified:
Frequency: 30 M Hz

Measured/Evaluated Properties
X : Temperature
Y : Elastic Constant, C(456)

Data Points:

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<th>Y</th>
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</thead>
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<td>1.000e+01</td>
<td>-3.060e+10</td>
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<td>-3.310e+10</td>
</tr>
<tr>
<td>5.200e+01</td>
<td>-3.310e+10</td>
</tr>
</tbody>
</table>
6.100e+01  -3.430e+10
7.700e+01  -3.440e+10
1.000e+02  -3.450e+10
1.190e+02  -3.460e+10
1.320e+02  -3.580e+10
1.490e+02  -3.360e+10
1.690e+02  -3.370e+10
1.990e+02  -3.490e+10
2.240e+02  -3.510e+10
2.420e+02  -3.400e+10
2.610e+02  -3.290e+10
2.720e+02  -3.180e+10
2.990e+02  -3.310e+10

**Comments on Data**
Data read from figure 4.

**Reference**
THIRD-ORDER ELASTIC CONSTANTS AND GRUENEISEN PARAMETERS OF SILICON AND GERMANIUM BETWEEN 3 AND 300 DEGREE K.
Philip, J. Breazeale, M. A.
J. APPL. PHYS.
54 (2), 752-7, 1983.
Figure 123 Elastic Constant, C(456) of Silicon
MATERIAL: Silicon

PROPERTY: Tensile Stress

****************************

Material Preparation
Crystal Growing Method:
Dislocation-free Czochralski crystals grown in various
atmospheres including vacuum, argon, N(2)-5% H(2) or
purified hydrogen.

Additional Preparation/Conditioning
Surface Treatment:
Samples prepared by grinding with No. 600 SiC grit etching in
CP-4 for 3-5 minutes.

Specimen Identification
Dimensions (Geometry):
Gauge-Section Length 2.5 cm
Width 1.5 mm
Thickness 3. mm
Additional Identifiers:
orientation along [001]

Measurement/Evaluation Method
Name/Description:
Tensile Loaded Bar Method
Tested with an Instron machine. A thermocouple placed about
2mm away from the specimen measured the temperature.
Parameters-Codified:
Pressure: 1.0e-03 mm Hg
Measurement Laboratory: Raytheon Company, Research Division

Measured/Evaluated Properties
X : Cross-Head Displacement
Y : Tensile Stress
Z1 : Temperature
Z2 : Cross-Head Speed

Data Points:

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<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
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<td>8.333e-05</td>
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<tr>
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<td>8.333e-05</td>
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<tr>
<td>7.000e-01</td>
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<td>8.333e-05</td>
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1.030e+00 1.040e+08 1.288e+03 8.333e-05
1.040e+00 7.845e+07 1.288e+03 8.333e-05
1.190e+00 3.982e+07 1.288e+03 8.333e-05
1.190e+00 3.521e+07 1.288e+03 8.333e-05
1.200e+00 3.168e+07 1.288e+03 8.333e-05
1.430e+00 2.824e+07 1.288e+03 8.333e-05
1.710e+00 2.658e+07 1.288e+03 8.333e-05
2.040e+00 2.540e+07 1.288e+03 8.333e-05
2.570e+00 2.481e+07 1.288e+03 8.333e-05
3.040e+00 2.599e+07 1.288e+03 8.333e-05
3.710e+00 2.540e+07 1.288e+03 8.333e-05
4.230e+00 2.599e+07 1.288e+03 8.333e-05

Comments on Data
Data read from Figure 3.
Initial portion essentially linear, at plastic elongation of
0.1-0.2%, stress reaches maximum.

Reference
MACROSCOPIC PLASTIC PROPERTIES OF DISLOCATION-FREE
GERMANIUM AND OTHER SEMICONDUCTOR CRYSTALS. I.
YIELD BEHAVIOR.
Patel, J. R. Chaudhuri, A. R.
J. APPL. PHYS.
Figure 124  Tensile Stress of Silicon
MATERIAL:  Silicon
PROPERTY:  Tensile Stress

********************************************************************

Material Preparation
Crystal Growing Method:
Dislocation-free Czochralski crystals grown in various
atmospheres including vacuum, argon, N(2)-5% H(2) or
purified hydrogen.

Additional Preparation/Conditioning
Surface Treatment:
Samples prepared by grinding with No. 600 SiC grit etching in
CP-4 for 3-5 minutes.

Specimen Identification
Dimensions (Geometry):
Gauge-Section Length  2.5  cm
Width  1.5  mm
Thickess  3.  mm
Additional Identifiers:
orientation along [001]

Additional Properties
Other Properties-Textual:
By increasing crystal growth diameter, dislocations from
1e03 to 1e04/cm[2] were incorporated.
Thermal shock was used to obtain dislocations approximately
1e05 per cm[2].
By bending and flattening, dislocations from 1e06 to 1e07 per
cm[2] were incorporated.

Measurement/Evaluation Method
Name/Description:
Tensile Loaded Bar Method
Tested with an Instron machine. A thermocouple placed about
2mm away from the specimen measured the temperature.
Parameters-Codified:
Pressure : 1.0e-03 mm Hg
Measurement Laboratory : Raytheon Company, Research Division

Measured/Evaluated Properties
X  : Cross-Head Displacement  %
Y  : Tensile Stress  Pa
Z1 : Dislocation Density  m
Z2 : Temperature
Z3 : Cross-Head Speed

Data Points :

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<tr>
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<th>Y</th>
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<th>Z2</th>
<th>Z3</th>
<th>K (m s⁻¹)</th>
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<td>0.000e+00</td>
<td>1.088e+03</td>
<td>8.333e-07</td>
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<td>3.200e-01</td>
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<td>1.088e+03</td>
<td>8.333e-07</td>
<td></td>
</tr>
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<td>5.100e-01</td>
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<td>1.088e+03</td>
<td>8.333e-07</td>
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Comments on Data  
Data read from Figure 8.

Reference  
MACROSCOPIC PLASTIC PROPERTIES OF DISLOCATION-FREE  
GERMANIUM AND OTHER SEMICONDUCTOR CRYSTALS. I.  
YIELD BEHAVIOR.  
Patel, J. R.  Chaudhuri, A. R.  
J. APPL. PHYS.  
Figure 125  Tensile Stress of Silicon
Material Preparation
Crystal Growing Method:
  Dislocation-free Czochralski crystals grown in various
  atmospheres including vacuum, argon, N(2)-5% H(2) or
  purified hydrogen.

Additional Preparation/Conditioning
Surface Treatment:
  Samples prepared by grinding with No. 600 SiC grit and
  etching in CP-4 for 3-5 minutes.

Specimen Identification
Dimensions (Geometry):
  Gauge-Section Length : 2.5 cm
  Width : 1.5 mm
  Thickness : 3. mm

Additional Identifiers:
  orientation along [001]

Measurement/Evaluation Method
Name/Description:
  Tensile Loaded Bar Method
  Tested with an Instron machine. A thermocouple placed about
  2mm away from the specimen measured the temperature.

Parameters-Codified:
  Pressure : 1.0e-03 mm Hg
  Measurement Laboratory : Raytheon Company, Research Division

Measured/Evaluated Properties
X : Temperature
Y : Tensile Strength, Lower Yield
Z1 : Cross-Head Speed

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Comments on Data
Data was digitized from Figure 14.
Data is called the flow stress in the paper.

Reference
MACROSCOPIC PLASTIC PROPERTIES OF DISLOCATION-FREE GERMANIUM AND OTHER SEMICONDUCTOR CRYSTALS. I.
YIELD BEHAVIOR.
Patel, J. R. Chaudhuri, A. R.
J. APPL. PHYS.
Figure 126 Tensile Strength, Lower Yield of Silicon
MATERIAL: Silicon

PROPERTY: Tensile Strength, Upper Yield

Material Preparation

Crystal Growing Method:
Dislocation-free Czochralski crystals grown in various atmospheres including vacuum, argon, N(2)-5% H(2) or purified hydrogen.

Additional Preparation/Conditioning

Surface Treatment:
Samples prepared by grinding with No. 600 SiC grit and etching in CP-4 for 3-5 minutes.

Specimen Identification

Dimensions (Geometry):
- Gauge-Section Length: 2.5 cm
- Width: 1.5 mm
- Thickness: 3.0 mm

Additional Identifiers:
orientation along [001]

Measurement/Evaluation Method

Name/Description:
- Tensile Loaded Bar Method
- Tested with an Instron machine. A thermocouple placed about 2mm away from the specimen measured the temperature.

Parameters-Codified:
- Pressure: 1.0e-03 mm Hg
- Measurement Laboratory: Raytheon Company, Research Division

Measured/Evaluated Properties

X : Temperature
Y : Tensile Strength, Upper Yield
Z1 : Cross-Head Speed

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Data was digitized from Figure 14.

**Reference**
MACROSCOPIC PLASTIC PROPERTIES OF DISLOCATION-FREE GERMANIUM AND OTHER SEMICONDUCTOR CRYSTALS. I. YIELD BEHAVIOR.
Patel, J. R. Chaudhuri, A. R.
J. APPL. PHYS.
Figure 127  Tensile Strength, Upper Yield of Silicon
MATERIAL:  Silicon: As doped 

PROPERTY:  Compressive Stress 

Material Preparation 
Crystal Growing Method :
Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment :
Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry) :
Thickness 2.2 mm
Width 2.2 mm
Length 4.5 mm
Orientation With Respect To Material : [111] Direction

Measurement/Evaluation Method
Name/Description :
Compression Loaded Bar Method
Compression test along <111> direction using a relaxometer.
Test done in an atmosphere of spectroscopically pure helium
Accuracy of the yield point measurements was +/- 3 pct.
Parameters-Codified :
Strain Rate : 6.8e-04 s[-1]

Measured/Evaluated Properties
X : Compressive Strain
Y : Compressive Stress
Z1 : Dopant Concentration
Z2 : Temperature

Data Points :

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**Comments on Data**
As-doping lowers the upper and lower yield points of silicon. Dopant concentration determined by Hall effect measurement.

**Reference**
SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON SINGLE CRYSTALS.
Mil'vidskii, M. G. Stolyarov, O. G.
Berkova, A. V.
FIZ. TVERD. TELA ( LENINGRAD )
6 ( 10 ), 3170-2, 1964.
(FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
6 ( 10 ), 2531-2, 1965)
Figure 128 Compressive Stress of Silicon: As doped
MATERIAL: Silicon: B doped

PROPERTY: Compressive Stress

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Material Preparation

Crystal Growing Method:
- Czochralski-grown, dislocation-free

Descriptors-Textual:
- Single-step annealing: 1073 K for 240 hrs

Specimen Identification

Number/Name: cz-b
Dimensions (Geometry):
- Length: 10.0 mm
- Width: 3.0 mm
- Thickness: 3.0 mm

Orientation With Respect To Material: [123] Direction

Additional Properties

Electrical Properties:
- Electrical Resistivity: 26.6 Ω cm
- Temperature: 298. K

Measurement/Evaluation Method

Name/Description:
- Compression Loaded Bar Method
  - Tests performed in air on an Instron machine (TTCM-L)
Parameters-Codified:
- Annealing Temperature: 1073. K
- Strain Rate: 8.3e-05 s⁻¹
- Temperature: 1073. K (test temperature)

Original Source Reference/Additional Information

Dopant concentration of P or B not given

Measured/Evaluated Properties

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Y : Compressive Stress
Z₁ : Temperature
Z₂ : Strain Rate
Data Points:

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Comments on Data
Data was digitized from figure 5.
Upper yield point drastically reduced after annealing.

Reference
COMPRESSSION TESTS OF HEAT-TREATED CZOCHRALSKI-GROWN
SILICON CRYSTALS.
Yasutake, K. Umeno, M. Kawabe, H.
PHYS. STATUS SOLIDI A
Figure 129  Compressive Stress of Silicon: B doped
Material Preparation
Crystal Growing Method:
Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment:
Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry):
Thickness 2.2 mm
Width 2.2 mm
Length 4.5 mm
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Compression test along <111> direction using a relaxometer.
Test done in an atmosphere of spectroscopically pure helium
Accuracy of the yield point measurements was +/- 3 pct.
Parameters-Codified:
Strain Rate: 6.8e-04 s[-1]

Measured/Evaluated Properties
X : Compressive Strain %
Y : Compressive Stress Pa
Z1 : Dopant Concentration m^-3
Z2 : Temperature K

Data Points:

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**Comments on Data**

B-doping increases the upper and lower yield points of silicon. Dopant concentration determined by Hall effect measurement.

**Reference**

SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON SINGLE CRYSTALS.

Mil'vidskii, M. G. Stolyarov, O. G.

Berkova, A. V.

FIZ. TVERD. TELA (LENINGRAD)
6 (10), 3170-2, 1964.

(For English translation see Sov. Phys.-Solid State, 6 (10), 2531-2, 1965)
Figure 130  Compressive Stress of Silicon: B doped
MATERIAL: Silicon: P doped

PROPERTY: Compressive Stress

****************************************

Composition
1.0E13 cm\(^{-3}\)
Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Floating-zone-grown boule, n-type

Additional Preparation/Conditioning
Surface Treatment:
Mechanically polished with one face remaining as-ground.
The specimens were cut using a diamond saw.

Specimen Identification
Dimensions (Geometry):
Length 9.2 mm
Width 3.8 mm
Thickness 3.8 mm
Orientation With Respect To Material: [100] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 700. \(\Omega \text{ cm}\)
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Silicon single crystals were deformed in compression at constant strain rates under hydrostatic pressure of 1500 MPa in a solid-confining-medium apparatus.
Parameters-Textual:
The specimen is in contact with a silver jacket. The diffusivity of silver in silicon is so small that during an experiment at the highest temperature (873 K) the penetration of silver is less than one micrometer.
Deformation below 673 K achieved by predeformation at a slower strain rate and temperature above 673 K to eliminate upper yield point. Normal testing then resumed after cooling to desired temperature.

Measured/Evaluated Properties
\( X \) : Compressive Strain  
\( Y \) : Compressive Stress  
\( Z_1 \) : Temperature  
\( Z_2 \) : Strain Rate

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Comments on Data

** predeformation run at 723 K followed by deformation at 573 K
Data was digitized from Figure 1.
Flow stress drops after a maximum and reaches an easy-glide stage
after 5 percent strain. A specimen deformed at 673 K fails shortly
after the maximum in the stress-strain curve. This gives a rough
value of 2800 MPa of the flow-stress under 1500 MPa hydrostatic
pressure. Extrapolation of flow-stress values to a failure stress
of 2800 MPa showed that it is not likely to be possible to induce
def ormation below 548 K under these testing conditions.

Reference
THE PLASTIC DEFORMATION OF SILICON BETWEEN 300
DEGREE C AND 600 DEGREE C.
Castaing, J. Veyssiere, P. Kubin, L. P.
Rabier, J.
PHILOS. MAG. A
44 ( 6 ), 1407-13, 1981.
Figure 131 Compressive Stress of Silicon: P doped
MATERIAL: Silicon

PROPERTY: Compressive Stress

*****

Material Preparation
Crystal Growing Method:
Crucible-grown Czochralski, dislocation-free
Descriptors-Textual:
One specimen was annealed in hydrogen for 4 hrs. at 973 K followed by 30 hrs. at 1273 K

Additional Preparation/Conditioning
Surface Treatment:
Specimens ground and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 0.5 cm
Width 0.5 cm
Thickness 1.25 cm
Orientation With Respect To Material: [123] Direction

Additional Properties
Other Properties-Numerical:
Oxygen Concentration 5.-8.e17 cm⁻³
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Test equipment not specified, probably Instron machine.
Tests done under forming gas (mixture of N(2) and H(2)).
Parameters-Codified:
Strain Rate: 6.7e-05 s⁻¹

Measured/Evaluated Properties
X : Compressive Strain
Y : Compressive Stress
Z1 : Temperature

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as-grown
Comments on Data
Data read from figure
CZ-crystals exhibit yield drop at 1073 K; magnitude of
drop decreases progressively with increasing deformation
temperature. The drop is absent at 1273 K.
At 1073 K, CZ-crystals exhibit a luders strain. This
strain is absent at 1173 K and higher.

Reference
LUEDERS BANDS IN DEFORMED SILICON CRYSTALS.
Mahajan, S. Brasen, D. Haasen, P.
ACTA METALL.
Figure 132 Compressive Stress of Silicon
MATERIAL: Silicon

PROPERTY: Compressive Stress

Material Preparation
Crystal Growing Method:
- Float-zone grown, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
- Specimens ground and chemically polished

Specimen Identification
Dimensions (Geometry):
- Length: 0.5 cm
- Width: 0.5 cm
- Thickness: 1.25 cm
Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
- Compression Loaded Bar Method
- Test equipment not specified, probably Instron machine.
- Tests done under forming gas (mixture of N(2) and H(2)).
Parameters-Codified:
- Strain Rate: 6.7e-05 s[-1]

Measured/Evaluated Properties
- X: Compressive Strain
- Y: Compressive Stress
- Z1: Temperature

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**Comments on Data**

Data read from figure
FZ-crystal exhibit yield drop at 1073 K; magnitude of drop decreases progressively with increasing deformation temperature.
The drop is absent at 1273 K.
The lducers strain at 1073 K is not very well defined as was the case for CZ-crystal.

**Reference**

LUEDERS BANDS IN DEFORMED SILICON CRYSTALS.
Mahajan, S. Brasen, D. Haasen, P.
ACTA METALL.
Figure 133: Compressive Stress of Silicon
MATERIAL: Silicon

PROPERTY: Compressive Stress

Vendor/Producer/Fabricator
POLYROD-grade polycrystals obtained from WACKER.

Conditioning History Of Alloys
Heat-Treatment Sequence: Tested in the as-received form

Material Preparation
Film Deposition Method:
Very-high purity polycrystals, POLYROD grade obtained by
Vapor deposition (CVD) on a single crystal core and grown to
a diameter of about 100 mm. Crystals exhibit a pronounced [110]
texture along the radial growth orientation

Specimen Identification
Dimensions (Geometry):
Length: 12. mm
Width: 4. mm
Thickness: 4. mm

Additional Identifiers:
Samples stressed perpendicular to growth axis

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
High-temperature apparatus mounted to Instron machine. Tests
done under reformed gas.
Parameters Codified:
Strain Rate: 7.0e-06 s[-1]

Measured/Evaluated Properties
X: Compressive Strain %
Y: Compressive Stress Pa
Z1: Temperature K

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**Comments on Data**
Data was digitized from Figure 2.
These stress-strain curves of as-grown samples are characterized by high yield stresses, still approximately 40 MPa at 0.9 melting temperature and small hardening rate, becoming negative at 1323 K, strain > 5.0e-02. Samples cut parallel to the radial growth direction are harder than samples cut parallel to the rod axis and have a smaller range of microplasticity.

Reference
MECHANICAL BEHAVIOR OF POLYCRYSTALS AND SINGLE CRYSTALS OF SILICON.
Omri, M. Michel, J. P. Tete, C. George, A.
STRENGTH OF METALS AND ALLOYS, VOL. 1, PROC. INT. CONF., ICSMA 7, 1985 1, 75-80, 1986.
(Edited by H. J. McQueen, J. P. Bailon, J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon Press: Elmsford, New York)
Figure 134  Compressive Stress of Silicon
MATERIAL: Silicon

PROPERTY: Compressive Stress

Vendor/Producer/Fabricator
POLYROD-grade polycrystals obtained from WACKER.

Conditioning History Of Alloys
Heat-Treatment Sequence: Tested in the as-received form

Material Preparation
Film Deposition Method:
Very-high purity polycrystals, POLYROD grade obtained by
Vapor deposition (CVD) on a single crystal core and grown to
a diameter of about 100 mm. Crystals exhibit a pronounced [110]
texture along the radial growth orientation

Specimen Identification
Dimensions (Geometry):
- Length: 12. mm
- Width: 4. mm
- Thickness: 4. mm

Additional Identifiers:
Sampels stressed along growth axis

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
High-temperature apparatus mounted to Instron machine.
Tests done under reformed gas.
Parameters-Codified:
Strain Rate: 7.0e-06 s\(^{-1}\)

Measured/Evaluated Properties
- X: Compressive Strain
- Y: Compressive Stress
- Z1: Temperature

Data Points:

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Comments on Data
Data was digitized from Figure 2.
These stress-strain curves of as-grown samples are characterized
by high yield stresses, still approximately 40 MPa at 0.9 melting
temperature and small hardening rate, becoming negative at 1323 K,
strain > 5.0e-02. Samples cut parallel to the radial growth
direction are harder than samples cut parallel to the rod axis
and have a smaller range of microplasticity.

Reference
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CRYSTALS OF SILICON.
Omri, M. Michel, J. P. Tete, C.
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1, 75-80, 1986.
( Edited by H. J. McQueen, J. P. Bailon,
J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon
Press: Elmsford, New York )
Figure 135 Compressive Stress of Silicon
MATERIAL: Silicon

PROPERTY: Compressive Stress

Vendor/Producer/Fabricator
POLYROD-grade polycrystals obtained from WACKER.

Conditioning History Of Alloys
Heat-Treatment Sequence: Annealed at 1653 K for 24 hrs.

Material Preparation
Film Deposition Method:
Very-high purity polycrystals, POLYROD grade obtained by
Vapor deposition (CVD) on a single crystal core and grown to
a diameter of about 100 mm. Crystals exhibit a pronounced [110]
texture along the radial growth orientation

Specimen Identification
Dimensions (Geometry):
Length 12. mm
Width 4. mm
Thickness 4. mm
Additional Identifiers:
Samples stressed perpendicular to growth axis.

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
High-temperature apparatus mounted to Instron machine.
Tests done under reformed gas.
Parameters-Codified:
Strain Rate: 7.0e-06 s[-1]

Measured/Evaluated Properties
X : Compressive Strain %
Y : Compressive Stress Pa
Z1 : Temperature K

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**Comments on Data**

Data was digitized from Figure 3.

A marked softening is observed for both orientations. At
1623 K the flow stress is not modified for samples cut parallel to the rod axis but is reduced by 25 percent for samples cut parallel to the radial growth direction. Hardening rate after annealing is larger–decreased softening at large strains.

Reference
MECHANICAL BEHAVIOR OF POLYCRYSTALS AND SINGLE CRYSTALS OF SILICON.
Omri, M. Michel, J. P. Tete, C.
George, A.
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CONF., ICSMA 7, 1985
1, 75-80, 1986.
(Edited by H. J. McQueen, J. P. Bailon, J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon Press: Elmsford, New York)
Figure 136  Compressive Stress of Silicon
MATERIAL: Silicon

PROPERTY: Compressive Stress

*********************************************************************************************

Vendor/Producer/Fabricator

POLYROD-grade polycrystals obtained from WACKER.

Conditioning History Of Alloys

Heat-Treatment Sequence: Annealed at 1653 K for 24 hrs.

Material Preparation

Film Deposition Method:

Very-high purity polycrystals, POLYROD grade obtained by Vapor deposition (CVD) on a single crystal core and grown to a diameter of about 100 mm. Crystals exhibit a pronounced [110] texture along the radial growth orientation

Specimen Identification

Dimensions (Geometry):

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Additional Identifiers:

Samples stressed along the growth axis.

Measurement/Evaluation Method

Name/Description:

Compression Loaded Bar Method

High-temperature apparatus mounted to Instron machine.

Tests done under reformed gas.

Parameters-Codified:

Strain Rate: 7.0e-06 s[-1]

Measured/Evaluated Properties

X: Compressive Strain

Y: Compressive Stress

Z1: Temperature

Data Points:

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7.570e+00  4.430e+07  1.623e+03  
8.630e+00  4.430e+07  1.623e+03

**Comments on Data**
Data was digitized from Figure 3.
A marked softening is observed for both orientations. At
1623 K the flow stress is not modified for samples cut
parallel to the rod axis but is reduced by 25 percent for
samples cut parallel to the radial growth direction. Hardening
rate after annealing is larger—decreased softening at large
strains.

**Reference**
MECHANICAL BEHAVIOR OF POLYCRYSTALS AND SINGLE
CRYSTALS OF SILICON.
Omri, M.  Michel, J. P.  Tete, C.
George, A.
STRENGTH OF METALS AND ALLOYS, VOL. 1, PROC. INT.
CONF., ICSMA 7, 1985
1, 75-80, 1986.
( Edited by H. J. McQueen, J. P. Bailon,
J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon
Press: Elmsford, New York )
Figure 137  Compressive Stress of Silicon
**Composition**
1.08 \( \text{cm}^{-3} \) Boron Dopant Concentration

**Material Preparation**
Crystal Growing Method:
- Float-zone grown, dislocation free, p-type, boron doped

Descriptors-Textual:
- Crystals cut with a diamond saw and mechanically polished with diamond paste (grade 1 micron)

**Specimen Identification**
Dimensions (Geometry):
- Length: 8.0 mm
- Width: 3.0 mm
- Thickness: 3.0 mm

Orientation With Respect To Material: [123] Direction

Additional Identifiers:
- Lateral faces were of \{111\} and \{541\} types

**Additional Properties**
Electrical Properties:
- Electrical Resistivity: 0.06 \( \Omega \text{cm} \)
- Temperature: 298. K

**Measurement/Evaluation Method**
Name/Description:
- Compression Tests of Pre-Strained Crystals
- Specimens deformed under argon atmosphere in an Instron testing machine equipped with a high temperature furnace.

Parameters-Codified:
- Pre-Strain Temperature: 1323. K
- Pre-Strain Rate, Plastic: 2.0-05 s\([-1]\) (pre-straining)

**Experimental Conditioning/Material Degradation**
Conditioning/Degradation/Environment: Preconditioning Treatment
Descriptors-Textual:
- Specimens pre-strained at 1323 K and 2.0-05 s\([-1]\] strain rate;
  it was stopped at a permanent strain of 1.5 pct. and cooled under load.

**Measured/Evaluated Properties**
X : Temperature
Y : Compressive Strength, Lower Yield
Z1 : Strain Rate

K
Pa
s⁻¹

Data Points :

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Comments on Data
Data read from figure
Pre-deformation at higher temperatures allows plastic deformation to take place at lower temperatures without brittle fracture. Within the experimental uncertainty, the yield strength of the intrinsic and p-type silicon appear to be in good agreement.

Reference
ON THE PLASTICITY OF SILICON BELOW 650 DEGREES C.
Demenet, J. L. Desoyer, J. C.
Rabier, J. Veyssiere, P.
SCR. METALL.
18 ( 1 ), 41-5, 1984.
Figure 138 Compressive Strength, Lower Yield of Silicon: B doped
Composition
9.14e cm
Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free, intrinsic
Descriptors-Textual:
Crystals cut with a diamond saw and mechanically polished
with diamond paste (grade 1 micron)

Specimen Identification
Dimensions (Geometry):
Length 8.0 mm
Width 3.0 mm
Thickness 3.0 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Lateral faces were of {111} and {541} types

Additional Properties
Electrical Properties:
Electrical Resistivity 5.0 Ω cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Compression Tests of Pre-Strained Crystals.
Specimens deformed under argon atmosphere in an Instron
testing machine equipped with a high temperature furnace.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Preconditioning Treatment
Descriptors-Textual:
Specimens pre-stained at 1323 K and 2.e-05 s[-1] strain rate;
it was stopped at a permanent strain of 1.5 pct. and cooled
under load.

Measurement/Evaluation Method
Parameters-Codified:
Pre-Strain Temperature: 1323. K
Pre-Strain Rate, Plastic: 2.e-05 s[-1] (pre-straining)
Measured/Evaluated Properties

X : Temperature  \( \text{K} \)
Y : Compressive Strength, Lower Yield  \( \text{Pa} \)
Z1 : Strain Rate  \( \text{s}^{-1} \)

Data Points:

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Comments on Data

Data read from Figure 1.
Pre-deformation at higher temperatures allows plastic deformation to take place at lower temperatures without brittle fracture. Within the experimental uncertainty, the yield strength of the intrinsic and p-type silicon appear to be in good agreement.

Reference

ON THE PLASTICITY OF SILICON BELOW 650 DEGREES C.
Demenet, J. L.  Desoyer, J. C.
Rabier, J.  Veyssiere, P.
SCR. METALL.
18 ( 1 ), 41-5, 1984.
Figure 139 Compressive Strength, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Compressive Strength, Lower Yield

************************************************************

Composition
6.e18 cm⁻³
Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free, n-type
Descriptors-Textual:
Crystals cut with a diamond saw and mechanically polished
with diamond paste (grade 1 micron)

Specimen Identification
Dimensions (Geometry):
  Length  8.0 mm
  Width   3.0 mm
  Thickness 3.0 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
  Lateral faces were of {111} and {541} types

Additional Properties
Electrical Properties:
  Electrical Resistivity 9.e-03 Ω cm
  Temperature 298. K

Measurement/Evaluation Method
Name/Description:
  Compression Loaded, Pre-Strained Bar Method
  Specimens deformed under argon atmosphere in an Instron
testing machine equipped with a high temperature furnace.
Parameters-Codified:
  Pre-Strain Temperature: 948.-1323 K
  Pre-Strain Rate, Plastic: 2.e-05 - 2.e-06 s[-1]

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Preconditioning Treatment
Descriptors-Textual:
  Specimens pre-strained at different temperatures and strain
  rates and cooled under load.

Measured/Evaluated Properties
  X : Temperature K

471
Y : Compressive Strength, Lower Yield
Z1 : Strain Rate
Z2 : Pre-Strain Temperature
Z3 : Pre-Strain Rate, Plastic

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Comments on Data:
Data read from figure
Pre-straining at different temperatures and strain rates did
not seem to have any appreciable effect on the yield strength.
a very strong difference in yield strengths between n-type and
intrinsic silicon is observed. The presence of phosphorus
in the n-type lowers the yield strength by a ratio of 3 to 4
as compared to the intrinsic type.

Reference:
ON THE PLASTICITY OF SILICON BELOW 650 DEGREES C.
Demenet, J. L. Desoyer, J. C.
Rabier, J. Veyssiere, P.
SCR. METALL.
18 (1), 41-5, 1984.
Figure 140  Compressive Strength, Lower Yield of Silicon, n-type
MATERIAL: Silicon: As doped

PROPERTY: Compressive Strength, Upper Yield

Material Preparation
Crystal Growing Method:
Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment:
Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry):
Thickness 2.2 mm
Width 2.2 mm
Length 4.5 mm
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Compression test along <111> direction using a relaxometer.
Test done in an atmosphere of spectroscopically pure helium
Accuracy of the yield point measurements was +/- 3 pct.
Parameters-Codified:
Strain Rate: 6.8e-04 s[-1]

Measured/Evaluated Properties
X: Dopant Concentration m⁻³
Y: Compressive Strength, Upper Yield Pa
Z₁: Temperature K

Data Points:

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<td>1.282e+26</td>
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<td>1.073e+03</td>
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Comments on Data
As-doping lowers the upper and lower yield points of silicon.
Dopant concentration determined by Hall effect measurement.

Reference
SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON SINGLE CRYSTALS.
Mil'vidskii, M. G.  Stolyarov, O. G.
Berkova, A. V.
FIZ. TVERD. TELA ( LENINGRAD )
6 ( 10 ), 3170-2, 1964.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
6 ( 10 ), 2531-2, 1965 )
Figure 141  Compressive Strength, Upper Yield of Silicon: As doped
MATERIAL: Silicon: B doped

PROPERTY: Compressive Strength, Upper Yield

Material Preparation
Crystal Growing Method:
Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment:
Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry):
Thickness 2.2 mm
Width 2.2 mm
Length 4.5 mm
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Compression test along <111> direction using a relaxometer.
Test done in an atmosphere of spectroscopically pure helium.
Accuracy of the yield point measurements was +/- 3 pct.
Parameters-Codified:
Strain Rate: 6.8e-04 s[-1]

Measured/Evaluated Properties
X : Dopant Concentration m⁻³
Y : Compressive Strength, Upper Yield Pa
Z1 : Temperature K

Data Points:

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Comments on Data
B-doping increases the yield point of silicon.
Dopant concentration determined by Hall effect measurement.
Reference
SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON
SINGLE CRYSTALS.
Mil'vidskii, M. G. Stolyarov, O. G.
Berkova, A. V.
FIZ. TVERD. TELA ( LENINGRAD )
6 (10), 3170-2, 1964.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
6 (10), 2531-2, 1965 )
Figure 142 Compressive Strength, Upper Yield of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Compressive Strength, Upper Yield

**Composition**

7.5e17 \text{ cm}^{-3} \quad \text{Oxygen Concentration}

10.6e16 \text{ cm}^{-3} \quad \text{Carbon Concentration}

**Material Preparation**

Crystal Growing Method:
Czochralski-grown, dislocation-free

Descriptors-Textual:
- Isothermal annealing in vacuum (5.e-06 torr) as follows
- Single-step annealing: 1073 K for 1 to 250 hrs.
- Two-step annealing: 1073 K for 1 to 240 hrs. followed by annealing at 1323 K for 10 hrs.

**Specimen Identification**

Number/Name: cz-b

Dimensions (Geometry):

- Length: 10.0 mm
- Width: 3.0 mm
- Thickness: 3.0 mm

Orientation With Respect To Material: [123] Direction

**Additional Properties**

Electrical Properties:
- Electrical Resistivity: 26.6 \text{ \Omega cm}
- Temperature: 298. \text{ K}

**Measurement/Evaluation Method**

Name/Description:
Compression Loaded Bar Method
Tests performed in air on an Instron machine (TTCM-L)

Parameters-Codified:
- Annealing Temperature: 1073. K
- Strain Rate: 8.3e-05 s[-1]
- Temperature: 1073. K (test temperature)

**Original Source Reference/Additional Information**

Dopant concentration of P or B not given

**Measured/Evaluated Properties**

X: Annealing Time \text{ s}
Y : Compressive Strength, Upper Yield
Z1 : Temperature
Z2 : Strain Rate

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Remarks:</th>
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Comments on Data
Data read from figures
Single annealing at 1073 K decreases the upper yield strength remarkably at larger annealing time. This is due to the introduction of large plate-like precipitates of SiO(2).

Reference
COMPRESSION TESTS OF HEAT-TREATED CZOCHRALSKI-GROWN SILICON CRYSTALS.
Yasutake, K. Umeno, M. Kawabe, H.
PHYS. STATUS SOLIDI A
Figure 143 Compressive Strength, Upper Yield of Silicon: B doped
**Composition**

- $8.0 \times 10^{-17} \text{ cm}^{-3}$: Oxygen Concentration
- $1.0 \times 10^{-16} \text{ cm}^{-3}$: Carbon Concentration

**Material Preparation**

- Crystal Growing Method:
  - Czochralski-grown, dislocation-free
- Descriptors-Textual:
  - Isothermal annealing in vacuum (5.0-6 torr) as follows
  - Single-step annealing: 1073 K for 1 to 250 hrs.
  - Two-step annealing: 1073 K for 1 to 240 hrs. followed by annealing at 1323 K for 10 hrs.

**Specimen Identification**

- Number/Name: cz-m
- Dimensions (Geometry):
  - Length: 10.0 mm
  - Width: 3.0 mm
  - Thickness: 3.0 mm
- Orientation With Respect To Material: [123] Direction

**Additional Properties**

- Electrical Properties:
  - Electrical Resistivity: 4.3 $\Omega \text{ cm}$
  - Temperature: 298 K

**Measurement/Evaluation Method**

- Name/Description:
  - Compression Loaded Bar Method
  - Tests performed in air on an Instron machine (TTCM-L)
- Parameters-Codified:
  - Annealing Temperature: 1073 K
  - Strain Rate: $8.3 \times 10^{-5} \text{ s}^{-1}$
  - Temperature: 1073 K (test temperature)

**Original Source Reference/Additional Information**

- Dopant concentration of P or B not given

**Measured/Evaluated Properties**

- $X$: Annealing Time $\text{ s}$
Y : Compressive Strength, Upper Yield  Pa
Z1 : Temperature  K
Z2 : Strain Rate  s^{-1}

Data Points :

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<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Remarks</th>
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</tbody>
</table>

Comments on Data
Data read from figures
Single annealing at 1073 K decreases the upper yield strength remarkably at larger annealing time. This is due to the introduction of large plate-like precipitates of SiO(2).

Reference
COMPRESSION TESTS OF HEAT-TREATED CZOCHRALSKI-GROWN SILICON CRYSTALS.
Yasutake, K., Umeno, M., Kawabe, H.
PHYS. STATUS SOLIDI A
Figure 144  Compressive Strength, Upper Yield of Silicon: B doped
Material Preparation
Crystal Growing Method:
Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment:
Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry):
 Thickness  2.2 mm
 Width     2.2 mm
 Length    4.5 mm
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Compression test along <111> direction using a relaxometer.
Test done in an atmosphere of spectroscopically pure helium
Accuracy of the yield point measurements was +/- 3 pct.

Measured/Evaluated Properties
X: Dopant Concentration $m^{-3}$
Y: Compressive Strength, Upper Yield $Pa$
Z1: Temperature $K$

Data Points:

<table>
<thead>
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<th>Z1</th>
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<td>2.515e+25</td>
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</table>

Comments on Data
P-doping does not seem to have a profound effect on the yield point of silicon.
Dopant concentration determined by Hall effect measurement.

Reference
SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON SINGLE CRYSTALS.
Mil'vidskii, M. G. Stolyarov, O. G.
Berkova, A. V.
FIZ. TVERD. TELA (LENINGRAD)
6 (10), 3170-2, 1964.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
6 (10), 2531-2, 1965 )
Figure 145  Compressive Strength, Upper Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Compressive Strength, Upper Yield

***********************************************************************************

**Composition**

<table>
<thead>
<tr>
<th>5.8e17</th>
<th>cm(^{-3})</th>
<th>Oxygen Concentration</th>
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<tbody>
<tr>
<td>42.8e16</td>
<td>cm(^{-3})</td>
<td>Carbon Concentration</td>
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</table>

**Material Preparation**

Crystal Growing Method:
Czochralski-grown, dislocation-free

Descriptors-Textual:
Isothermal annealing in vacuum (5.e-06 torr) as follows
Single-step annealing: 1073 K for 1 to 250 hrs.
Two-step annealing: 1073 K for 1 to 240 hrs. followed by annealing at 1323 K for 10 hrs.

**Specimen Identification**

Number/Name: cz-a

Dimensions (Geometry):

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mm

Orientation With Respect To Material: [123] Direction

**Additional Properties**

Electrical Properties:
Electrical Resistivity: 2.9 \(\Omega \text{ cm}\)
Temperature: 298. \(K\)

**Measurement/Evaluation Method**

Name/Description:
Compression Loaded Bar Method
Tests performed in air on an Instron machine (TTCM-L)

Parameters-Codified:
Annealing Temperature: 1073. \(K\)
Annealing Time: 1-250 hrs.
Strain Rate: 8.3e-05 s\([-1]\)
Temperature: 1073. \(K\) (test temperature)

**Original Source Reference/Additional Information**

Dopant concentration of P or B not given

**Measured/Evaluated Properties**

\(X\) : Annealing Time \(s\)
Y : Compressive Strength, Upper Yield  
Z1 : Temperature  
Z2 : Strain Rate  

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Remarks</th>
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Comments on Data

Data read from figure.
Upper yield strength did not change with annealing time for single-step annealing while decreased with increasing time for double-step annealing.

Reference

COMPRESSION TESTS OF HEAT-TREATED CZOHRALSKI-GROWN SILICON CRYSTALS.
Yasutake, K.  Umeno, M.  Kawabe, H.
PHYS. STATUS SOLIDI A
Figure 146 Compressive Strength, Upper Yield of Silicon: P doped
Material Preparation
Crystal Growing Method:
- Czochralski method, dislocation-free.

Additional Preparation/Conditioning
Surface Treatment:
- Samples polished mechanically and chemically.

Specimen Identification
Dimensions (Geometry):
- Thickness: 2.2 mm
- Width: 2.2 mm
- Length: 4.5 mm
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method
Name/Description:
- Compression Loaded Bar Method
- Compression test along <111> direction using a relaxometer.
- Test done in an atmosphere of spectrosopically pure helium
- Accuracy of the yield point measurements was +/- 3 pct.

Measured/Evaluated Properties
X: Dopant Concentration
Y: Compressive Strength, Upper Yield
Z1: Temperature

Data Points:

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Comments on Data
Sb-doping in the range $1.0 \times 10^{17}$-$1.0 \times 10^{18}$ cm$^{-3}$ appear to increase the yield point of silicon. Dopant concentration determined by Hall effect measurement. Concentrations above $1.0 \times 10^{18}$ lower the yield point.

**Reference**

SOME MECHANICAL PROPERTIES OF STRONGLY DOPED SILICON SINGLE CRYSTALS.
Mil'vidskii, M. G. Stolyarov, O. G.
Berkova, A. V.
FIZ. TVERD. TELA ( LENINGRAD )
6 ( 10 ), 3170-2, 1964.
( FOR ENGLISH TRANSLATION SEE SOV. PHYS.-SOLID STATE,
6 ( 10 ), 2531-2, 1965 )
Figure 147 Compressive Strength, Upper Yield of Silicon: Sb doped
**Material Preparation**

Crystal Growing Method:
Czochralski grown, dislocation free

**Specimen Identification**

Orientation With Respect To Material: [123] Direction

**Measurement/Evaluation Method**

Name/Description:
Resolved Shear From Tensile Loading Test
Instron machine used

**Measured/Evaluated Properties**

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6.272e+01  5.636e+07  1.100e-04  1.173e+03

**Comments on Data**
Data read from Figure 3.
Deformation takes place by propagation of Luders bands in yield region.

**Reference**
SOLUTION EFFECTS ON THE MECHANICAL BEHAVIOR AND THE DISLOCATION MOBILITY IN SILICON CRYSTALS.
Sumino, K. Yonenaga, I. Harada, H.
Imai, M.
DISLOCAT. MODELL. PHYS. SYST., PROC. INT. CONF., 1980 212-6, 1981.
(Edited by M. F. Ashby, R. Bullough, C. S. Hartley and J. P. Hirth; Pergamon Press: New York)
Figure 148 Shear Stress, Resolved of Silicon, intrinsic
MATERIAL:  Silicon, intrinsic

PROPERTY:  Shear Stress, Resolved

Material Preparation
Crystal Growing Method:
  Float zone grown, dislocation free

Specimen Identification
Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
  Resolved Shear From Tensile Loading Test
  Instron machine used

Measured/Evaluated Properties
X : Shear Strain, Resolved
Y : Shear Stress, Resolved
Z1 : Shear Strain Rate, Resolved
Z2 : Temperature

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Comments on Data
Data read from Figure 3.
Deformation takes place by propagation of Luders bands in yield region.

Reference
SOLUTION EFFECTS ON THE MECHANICAL BEHAVIOR AND THE DISLOCATION MOBILITY IN SILICON CRYSTALS.
Sumino, K. Yonenaga, I. Harada, H.
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DISLOCAT. MODELL. PHYS. SYST., PROC. INT. CONF., 1980 212-6, 1981.
(Edited by M. F. Ashby, R. Bullough, C. S. Hartley and J. P. Hirth; Pergamon Press: New York)
Figure 149 Shear Stress, Resolved of Silicon, intrinsic
MATERIAL: Silicon: P doped

PROPERTY: Shear Stress, Resolved

Composition
1.e18 cm⁻³ Oxygen Concentration
2.e16 cm⁻³ Carbon Concentration

Vendor/Producer/Fabricator
KOFU Works of Hitachi Ltd.

Material Preparation
Crystal Growing Method:
Czochralski grown, dislocation free, n-type
Grown with diameter of 76 mm in the [111] direction.

Additional Preparation/Conditioning
Surface Treatment:
Surface layers polished and removed to depth more than
250 microns.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 7-9 Ω cm
Temperature 298 K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Test conducted in vacuum using Instrom machine mounted to high
temperature apparatus. Resolved shear properties derived from
measured data.
Parameters-Codified:
Pressure: 1.333e-03 Pa
Shear Strain, Resolved: 1.1e-04 s⁻1
Temperature: 1173. K

Measured/Evaluated Properties
X : Shear Strain, Resolved %
Y : Shear Stress, Resolved Pa
Z1 : Temperature K
Z2 : Shear Strain Rate, Resolved s⁻¹
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Comments on Data
Deformation preceded by means of the propagation of Luders bands in the yield region.

Reference
MECHANICAL BEHAVIOR OF CZOCHRALSKI-SILICON CRYSTALS AS AFFECTED BY PRECIPITATION AND DISSOLUTION OF OXYGEN ATOMS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS.
Figure 150 Shear Stress, Resolved of Silicon: P doped
Material: Silicon: P doped

Property: Shear Stress, Resolved

-------------------------------

**Composition**

- 1.e18 \( \text{cm}^{-3} \) Oxygen Concentration
- 2.e16 \( \text{cm}^{-3} \) Carbon Concentration

**Vendor/Producer/Fabricator**

KOFU Works of Hitachi Ltd.

**Material Preparation**

Crystal Growing Method:
- Czochralski grown, dislocation free, n-type
- Grown with diameter of 76 mm in the [111] direction.

Descriptors-Textual:
- Annealed at various temperatures for 24 hours.

**Additional Preparation/Conditioning**

Surface Treatment:
- Surface layers polished and removed to depth more than 250 microns.

**Specimen Identification**

Orientation With Respect To Material: [123] Direction

**Additional Properties**

Electrical Properties:
- Electrical Resistivity: 7-9 \( \Omega \text{ cm} \)
- Temperature: 298 \( \text{K} \)

**Measurement/Evaluation Method**

Name/Description:
- Shear Response Under Tensile Loading
  Test conducted in vacuum using Instrom machine mounted to high temperature apparatus. Resolved shear properties derived from measured data.

Parameters-Codified:
- Pressure: 1.e-05 Torr
- Shear Strain, Resolved: 1.1e-04 s[-1]
- Temperature: 1173. K
- Annealing Time: 24 hrs.

**Measured/Evaluated Properties**

X: Shear Strain, Resolved %
Y: Shear Stress, Resolved  
Z1: Annealing Temperature  
Z2: Temperature  
Z3: Shear Strain Rate, Resolved  

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**Comments on Data**
Annealing at 1323 K drastically reduces the yield strength throughout all deformation stages.
Annealing at 1448 and 1593 K does not affect the magnitude of the upper yield of the stress significantly.

**Reference**
MECHANICAL BEHAVIOR OF CZOCHRALSKI-SILICON CRYSTALS AS AFFECTED BY PRECIPITATION AND DISSOLUTION OF OXYGEN ATOMS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS.
Figure 151  Shear Stress, Resolved of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Stress, Resolved

*****************************************************************************

Composition
1.e18 cm\(^{-3}\) Oxygen Concentration
2.e16 cm\(^{-3}\) Carbon Concentration

Vendor/Producer/Fabricator
KOFU Works of Hitachi Ltd.

Material Preparation
Crystal Growing Method:
Czochralski grown, dislocation free, n-type
Grown with diameter of 76 mm in the [111] direction.
Descriptors-Textual:
Annealed at 1323. K for various times.

Additional Preparation/Conditioning
Surface Treatment:
Surface layers polished and removed to depth more than 250 microns.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity
Temperature
7-9 Ω cm
298 K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Test conducted in vacuum using Instrom machine mounted to high temperature apparatus. Resolved shear properties derived from measured data.
Parameters-Codified:
Pressure: 1.e-05 Torr
Shear Strain, Resolved: 1.1e-04 s[-1]
Temperature: 1173. K
Annealing Temperature: 1323. K

Measured/Evaluated Properties
X : Shear Strain, Resolved %
Y : Shear Stress, Resolved  \[ \text{Pa} \]
Z1 : Annealing Time  \[ \text{s} \]
Z2 : Temperature  \[ \text{K} \]
Z3 : Shear Strain Rate, Resolved  \[ \text{s}^{-1} \]

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**Comments on Data**
Specimens show rapid softening with increase of annealing time.

**Reference**
MECHANICAL BEHAVIOR OF CZOCHRALSKI-SILICON CRYSTALS AS AFFECTED BY PRECIPITATION AND DISSOLUTION OF OXYGEN ATOMS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS.
Figure 152  Shear Stress, Resolved of Silicon: P doped
MATERIAL: Silicon, n-type

PROPERTY: Shear Stress, Resolved

Vendor/Producer/Fabricator
POLYROD-grade single crystals obtained from WACKER.

Conditioning History Of Alloys
Heat-Treatment Sequence: Tested in the as-received form

Material Preparation
Crystal Growing Method:
Single crystals obtained by floating-zone technique from
POLYROD n-type silicon, dislocation-free.

Specimen Identification
Dimensions (Geometry):
Length 14. mm
Width 4.25 mm
Thickness 4.25 mm
Orientation With Respect To Material: [110] Direction
Additional Identifiers:
Samples stressed along the growth axis.

Additional Properties
Electrical Properties:
Electrical Resistivity > 5.0 Ω cm
Temperature 298.0 K

Measurement/Evaluation Method
Name/Description:
tests.
Shear Response Under Compressive Loading
High-temperature apparatus mounted to Instron machine.
Tests done under reformed gas.
Shear properties derived from measured data.
Parameters-Codified:
Shear Strain Rate, Resolved: 6.0e-06 s[-1]

Measured/Evaluated Properties
X: Compressive Strain, True %
Y: Shear Stress, Resolved Pa
Z1: Temperature K

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**Comments on Data**
Data was digitized from Figure 5.
A stress peak is observed at $T<1223$ K and a stage of easy glide seems to be present, with a slightly higher hardening rate.

Reference
MECHANICAL BEHAVIOR OF POLycRySTALS AND SINGLE CRYSTALS OF SILICON.
Omri, M. Michel, J. P. Tete, C.
George, A.
STRENGTH OF METALS AND ALLOYS, VOL. 1, PROC. INT. CONF., ICSMA 7, 1985
1, 75-80, 1986.
(Edited by H. J. McQueen, J. P. Bailon,
J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon Press: Elmsford, New York)
Figure 153 Shear Stress, Resolved of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Stress, Resolved

********************************************************************************

Vendor/Producer/Fabricator
POLYROD-grade single crystals obtained from WACKER.

Conditioning History Of Alloys
Heat-Treatment Sequence: Tested in the as-received form

Material Preparation
Crystal Growing Method:
Single crystals obtained by floating-zone technique from
POLYROD n-type silicon, dislocation-free.

Specimen Identification
Dimensions (Geometry):
Length 14. mm
Width 4.25 mm
Thickness 4.25 mm
Orientation With Respect To Material: [100] Direction
Additional Identifiers:
Samples stressed along the growth axis.

Additional Properties
Electrical Properties:
Electrical Resistivity > 5.0 Ω cm
Temperature 298.0 K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature apparatus mounted to Instron machine.
Tests done under reformed gas.
Shear properties derived from measured data.
Parameters-Codified:
Shear Strain Rate, Resolved: 6.0e-06 s[-1]

Measured/Evaluated Properties
X: Compressive Strain, True %
Y: Shear Stress, Resolved Pa
Z1: Temperature K

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Comments on Data
Data was digitized from Figure 6.
A stress peak is observed at T<1223 K and a stage of easy glide
seems to be present, with a slightly higher hardening rate.

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J. I. Dickson, J. J. Jonas and M. G. Akben; Pergamon
Press: Elmsford, New York )
Figure 154 Shear Stress, Resolved of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Stress, Resolved

*****************************************

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
- Float-zone technique
- Crystal grown in a high purity argon gas atmosphere.

Descriptors-Textual:
- Dislocation density controlled by deformation at 1173 K and various strains (less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
- Electrical Resistivity: 460. Ω cm
- Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
- Shear Response Under Tensile Loading

Parameters-Textual:
- Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of luders bands occurred.

Parameters-Codified:
- Temperature: 1073. K
- Strain Rate: 1.2e-04 s[-1]

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Descriptors-Numerical:
- Pressure: 1.e-04 torr

Measured/Evaluated Properties
- X: Shear Strain, Resolved
- Y: Shear Stress, Resolved
- Z1: Dislocation Density
- Z2: Strain Rate

524
Z3: Temperature

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**Comments on Data**

For specimens showing no yield point phenomenon, the strain at lower yield point is taken as that of intersection of extensions of elastic region and of stress-strain curve. Yield behavior strongly affected by initial density of dislocations.

**Reference**

DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.

Yonenaga, I. Sumino, K.

PHYS. STATUS SOLIDI A
Figure 155  Shear Stress, Resolved of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Stress, Resolved

***********************************************************

Vendor/Producer/Fabricator
Wacker

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
\{111\} and \{541\} side faces cut with a diamond saw and
diamond polished (1/4 micron)

Specimen Identification
Dimensions (Geometry):
Length 14. mm
Thickness 4.25 mm
Width 4.25 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Specimen oriented to obtain a single slip deformation
along \{111\} planes and <101> directions

Additional Properties
Electrical Properties:
Electrical Resistivity >5. Ω cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature compression stage apparatus mounted on an
Instron machine. A continuous flow of forming gas (10 pct. H(2),
90 pct. N(2)) maintained during each test. Curves of resolved
shear stress - strain derived from the recorded data.
Parameters-Codified:
Shear Strain Rate, Resolved : 2.e-05 s[-1]

Measured/Evaluated Properties
X : Shear Strain, Resolved %
Y : Shear Stress, Resolved Pa
Z1 : Temperature K
Z2 : Shear Strain Rate, Resolved  \( s^{-1} \)

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**Comments on Data**

Data read from figures.
The curves exhibit the usual shape, with an initial peak stress followed by the three stages characteristic of f.c.c. crystals.

**Reference**

ON THE YIELD POINT OF FLOATING-ZONE SILICON SINGLE CRYSTALS. I. YIELD STRESSES AND ACTIVATION PARAMETERS.
Omri, M. Tete, C. Michel, J. P.
George, A.
PHILOS. MAG. A
Figure 156  Shear Stress, Resolved of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Stress, Resolved

****************************

Vendor/Producer/Fabricator
Wacker

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free
Descriptors-Textual:
crystal pre-strained to extend temperature range towards lower range

Additional Preparation/Conditioning
Surface Treatment:
\{111\} and \{541\} side faces cut with a diamond saw and diamond polished (1/4 micron)

Specimen Identification
Dimensions (Geometry):
Length 14. mm
Thickness 4.25 mm
Width 4.25 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Specimen oriented to obtain a single slip deformation along \{111\} planes and \langle101\rangle directions

Additional Properties
Electrical Properties:
Electrical Resistivity >5. \(\Omega\) cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature compression stage apparatus mounted on an Instron machine. A continuous flow of forming gas (10\% H(2), 90\% N(2)) maintained during each test. Curves of resolved shear stress - strain derived from the recorded data.
Parameters-Codified:
Pre-Strain Rate, Plastic: 7.e-02 pct. (shear)
Shear Strain Rate, Resolved: 2.e-05 s\[-1\] (pre-straining)
Pre-Strain Temperature: 1323. K
**Measured/Evaluated Properties**

X : Shear Strain, Resolved
Y : Shear Stress, Resolved
Z1 : Temperature
Z2 : Shear Strain Rate, Resolved

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Comments on Data
Best compromise for prestraining was found at 2.e-05 s[-1]
and 1323 K to create as many mobile dislocations as possible
but keep hardening as low as possible.
At 818 K, (lowest temp), silicon can be deformed without
cracks.

Reference
ON THE YIELD POINT OF FLOATING-ZONE SILICON SINGLE
CRYSTALS. I. YIELD STRESSES AND ACTIVATION
PARAMETERS.
Omri, M. Tete, C. Michel, J. P.
George, A.
PHILOS. MAG. A
Figure 157  Shear Stress, Resolved of Silicon, n-type
MATERIAL: Silicon: B doped

PROPERTY: Shear Strength, Resolved, Lower Yield

*******************************************************

Vendor/Producer/Fabricator
Wacker Chemie, Munchen

Material Preparation
Crystal Growing Method:
Floating zone, p-type, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N2, 8 percent H2) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
X : Boron Dopant Concentration m^{-3}
Y : Shear Strength, Resolved, Lower Yield Pa
Z1 : Temperature K
Z2 : Shear Strain Rate, Resolved s^{-1}

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Comments on Data
Data was digitized from Figure 4.
Boron-doping causes an increase in lower yielded strength

Reference
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT
OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 158 Shear Strength, Resolved, Lower Yield of Silicon: B doped
Composition
1.25e20 cm\(^{-3}\) Boron Dopant Concentration

Vendor/Producer/Fabricator
Wacker Chemie, Munchen

Material Preparation
Crystal Growing Method:
Floating zone, p-type, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N\(_2\), 8 percent H\(_2\)) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
X : Shear Strain Rate, Resolved s\(^{-1}\)
Y : Shear Strength, Resolved, Lower Yield Pa
Z1 : Temperature K

Data Points:

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4.800e-03  1.290e+07  1.373e+03
1.200e-02  1.770e+07  1.373e+03

Comments on Data
Data was digitized from Figure 1.
Lower yield strength curve at 1173 K intersects the
1373 K curve at a strain rate of 0.1e-03/s. Anomalous behavior
is due to solubility of boron in Silicon. As diffusion not being
negligible at 1173 K, certain amount of boron precipitates and
solute level is decreased. Corresponding decrease of lower yield
stress shows that impurities in solute state mainly responsible for
observed effects and few precipitated particles do not have much
influence on yield point.

Reference
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT
OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 159 Shear Strength, Resolved, Lower Yield of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Shear Strength, Resolved, Lower Yield

******************************************************************************

Composition
4.0e19 \text{ cm}^{-3} \quad \text{Boron Dopant Concentration}

Vendor/Producer/Fabricator
Wacker Chemie, Munchen

Material Preparation
Crystal Growing Method:
Floating zone, p-type, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):

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Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent \text{ N}_2, 8 percent \text{ H}_2) or
argon in Instron machine using high temperature compression apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
\begin{align*}
X & : \text{Shear Strain Rate, Resolved} \quad \text{s}^{-1} \\
Y & : \text{Shear Strength, Resolved, Lower Yield} \quad \text{Pa} \\
Z1 & : \text{Temperature} \quad \text{K}
\end{align*}

Data Points:

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Y & = 1.000e+07 \\
Z1 & = 1.173e+03
\end{align*}
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| 1.200e-03 | 1.780e+07 | 1.173e+03 |
| 4.800e-04 | 7.100e+06 | 1.273e+03 |
| 1.200e-03 | 1.080e+07 | 1.273e+03 |
| 2.400e-03 | 1.210e+07 | 1.273e+03 |
| 4.700e-03 | 1.520e+07 | 1.273e+03 |
| 4.800e-05 | 3.800e+06 | 1.373e+03 |
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| 5.000e-03 | 1.080e+07 | 1.373e+03 |
| 1.300e-02 | 1.350e+07 | 1.373e+03 |

**Comments on Data**

Data was digitized from Figure 2.
Lower yielded strength at 1173 K curve intersects the
1373 K curve at strain rate of 0.1e-03/s. Anomalous behavior due
to solubility of boron in Silicon. Diffusion not being negligible
at 1173 K, certain amount of boron precipitates and solute level
decreased. Corresponding decrease of lower yield stress shows that
impurities in solute state mainly responsible for observed effects
and few precipitated particles do not have much influence
on yield strength

**Reference**

THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT
OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 160  Shear Strength, Resolved, Lower Yield of Silicon: B doped
Composition
6.0e17 cm⁻³ Oxygen Concentration

Vendor/Producer/Fabricator
Sony Corp. and Komatsu Electronic Metals Co.

Material Preparation
Crystal Growing Method:
Czochralski grown
Descriptors-Textual:
Prior to tensile tests all specimens were subjected to annealing
at 1573 K for 2 hours followed by rapid cooling at a rate of 150 °C
per minute to eliminate possible segregation of carbon and/or
oxygen, and also to homogenize the distribution of defects.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Other Properties-Numerical:
Dislocation Density 1.0e06 cm⁻²

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tests conducted in vacuum using an Instron machine.
Dislocation density determined by etch-pit technique.
Resolved shear properties derived from recorded data.
Carbon and oxygen concentrations determined by IR absorption.
Parameters-Codified:
Shear Strain Rate, Resolved: 1.1e-04 s⁻¹
Pressure: 1.33e-02 pa

Measured/Evaluated Properties
X: Carbon Concentration m⁻³
Y: Shear Strength, Resolved, Lower Yield Pa
Z₁: Temperature K

Data Points:
X Y Z₁
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<td>1.073e+03</td>
</tr>
<tr>
<td>1.700e+23</td>
<td>1.320e+07</td>
<td>1.073e+03</td>
</tr>
<tr>
<td>2.500e+23</td>
<td>1.430e+07</td>
<td>1.073e+03</td>
</tr>
<tr>
<td>0.000e+00</td>
<td>7.800e+06</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>1.700e+23</td>
<td>8.000e+06</td>
<td>1.173e+03</td>
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<tr>
<td>2.500e+23</td>
<td>9.300e+06</td>
<td>1.173e+03</td>
</tr>
</tbody>
</table>

**Comments on Data**
Lower yield strength does not seem to depend on carbon content.

**Reference**
ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS., PART 2
23 (8), 590-2, 1984.
Figure 161 Shear Strength, Resolved, Lower Yield of Silicon: C doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

Composition
1.0E13 cm\(^{-3}\)
Phosphorus Dopant Concentration

Material Preparation
Crystal Growing Method:
Floating-zone-grown boule, n-type

Additional Preparation/Conditioning
Surface Treatment:
Mechanically polished with one face remaining as-ground.
The specimens were cut using a diamond saw.

Specimen Identification
Dimensions (Geometry):
Length 9.2 mm
Width 3.8 mm
Thickness 3.8 mm
Orientation With Respect To Material: [100] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 700. \(\Omega\) cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Silicon single crystals were deformed in compression at constant strain rates under hydrostatic pressure of 1500 MPa in a solid-confining-medium apparatus.
Parameters-Textual:
The specimen is in contact with a silver jacket. The diffusivity of silver in silicon is so small that during an experiment at the highest temperature (873 K) the penetration of silver is less than one micrometer.
Deformation below 673 K achieved by predeformation at a slower strain rate and temperature above 673 K to eliminate upper yield point. Normal testing then resumed after cooling to desired temperature.

Measured/Evaluated Properties
X : Temperature  
Y : Shear Strength, Resolved, Lower Yield  
Z1 : Shear Strain Rate, Resolved

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.870e+02</td>
<td>1.001e+09</td>
<td>5.000e-06</td>
</tr>
<tr>
<td>5.870e+02</td>
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</tr>
<tr>
<td>6.870e+02</td>
<td>4.024e+08</td>
<td>5.000e-06</td>
</tr>
<tr>
<td>7.350e+02</td>
<td>2.509e+08</td>
<td>5.000e-06</td>
</tr>
<tr>
<td>6.870e+02</td>
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<td>5.000e-05</td>
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<td>7.390e+02</td>
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<tr>
<td>7.820e+02</td>
<td>2.690e+08</td>
<td>5.000e-05</td>
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<tr>
<td>8.820e+02</td>
<td>5.500e+07</td>
<td>5.000e-05</td>
</tr>
</tbody>
</table>

**Comments on Data**

Data was digitized from Figure 2.
A graph of log yield strength against T suggests a change of slope occurring at 873-923 K. This is taken as the transition temperature. This change of slope could also denote that different thermally activated mechanisms govern the deformation rate at large stresses and low temperatures on one hand and at low stresses and high temperatures on the other.
Measurement uncertainty estimated to be +/- 50 MPa, mostly due to friction.

**Reference**

THE PLASTIC DEFORMATION OF SILICON BETWEEN 300 DEGREE C AND 600 DEGREE C.
Castaing, J. Veyssiere, P. Kubin, L. P.
Rabier, J.
PHILOS. MAG. A
44 (6), 1407-13, 1981.
Figure 162 Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

Vendor/Producer/Fabricator
Wacker Chemie, Munchen

Material Preparation
Crystal Growing Method:
Floating zone, p-type, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N₂, 8 percent H₂) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.
Parameters-Codified:
Shear Strain Rate, Resolved: 4.8e-03 s⁻¹

Measured/Evaluated Properties
X: Temperature K
Y: Shear Strength, Resolved, Lower Yield Pa⁻³
Z1: Phosphorus Dopant Concentration m⁻³
Z2: Shear Strain Rate, Resolved s⁻¹

Data Points:

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<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
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</thead>
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<td>4.800e-03</td>
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</tbody>
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1.273e+03  1.250e+07  5.000e+25  4.800e-03
1.224e+03  1.640e+07  5.000e+25  4.800e-03
1.173e+03  2.150e+07  5.000e+25  4.800e-03
1.377e+03  8.100e+06  1.000e+26  4.800e-03
1.270e+03  1.330e+07  1.000e+26  4.800e-03
1.173e+03  2.300e+07  1.000e+26  4.800e-03
1.370e+03  1.080e+07  1.350e+26  2.400e-04
1.271e+03  1.330e+07  1.350e+26  2.400e-04
1.171e+03  1.730e+07  1.350e+26  2.400e-04
1.070e+03  2.290e+07  1.350e+26  2.400e-04
1.372e+03  8.100e+06  1.000e+26  2.400e-04
1.271e+03  1.010e+07  1.000e+26  2.400e-04
1.171e+03  1.350e+07  1.000e+26  2.400e-04
1.070e+03  1.790e+07  1.000e+26  2.400e-04
1.372e+03  6.300e+06  8.000e+25  2.400e-04
1.320e+03  7.700e+06  8.000e+25  2.400e-04
1.271e+03  7.900e+06  8.000e+25  2.400e-04
1.222e+03  9.500e+06  8.000e+25  2.400e-04
1.171e+03  1.070e+07  8.000e+25  2.400e-04

Comments on Data
At high strain rates the activation energy of dislocation velocity measured by lower yield strength was found to be 2 eV for P-doped Silicon. At low strain rates, the lower yield becomes independent of strain rate.

Reference
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 163 Shear Strength, Resolved, Lower Yield of Silicon: P doped
**Material:** Silicon: P doped

**Property:** Shear Strength, Resolved, Lower Yield

**Composition**

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Unit</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>2.5e14</td>
<td>cm(^{-3})</td>
<td>Phosphorus Dopant Concentration</td>
</tr>
<tr>
<td>1.0e16</td>
<td>cm(^{-3})</td>
<td>Carbon Concentration</td>
</tr>
<tr>
<td>1.3e16</td>
<td>cm(^{-3})</td>
<td>Oxygen Concentration</td>
</tr>
</tbody>
</table>

**Material Preparation**

Crystal Growing Method:
- Float-zone grown, n-type, dislocation-free

**Additional Preparation/Conditioning**

Surface Treatment:
- Chemically polished

**Specimen Identification**

Dimensions (Geometry):
- Length: 15. mm
- Width: 3. mm
- Thickness: 3. mm

Orientation With Respect To Material: [123] Direction

Additional Identifiers:
- Slip system along {111} planes and <101> directions

**Additional Properties**

Electrical Properties:
- Electrical Resistivity: 16. \(\Omega\) cm
- Temperature: 298. K

**Measurement/Evaluation Method**

Name/Description:
- Compression Loaded Bar Method
- Testing machine not specified, probably Instron machine.
- Resolved shear properties derived from measured stress-strain curves.

Parameters-Codified:
- Pressure: 1.e-06 torr

**Measured/Evaluated Properties**

- \(X\): Temperature \(K\)
- \(Y\): Shear Strength, Resolved, Lower Yield \(Pa\)
- \(Z1\): Shear Strain Rate, Resolved \(s^{-1}\)
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
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</thead>
<tbody>
<tr>
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<td>1.450e-04</td>
<td>smoothed data</td>
</tr>
<tr>
<td>1.141e+03</td>
<td>7.940e+06</td>
<td>1.450e-04</td>
<td></td>
</tr>
<tr>
<td>1.174e+03</td>
<td>6.230e+06</td>
<td>1.450e-04</td>
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</tr>
<tr>
<td>1.210e+03</td>
<td>4.800e+06</td>
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</tr>
<tr>
<td>1.247e+03</td>
<td>3.710e+06</td>
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</tr>
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<td>1.288e+03</td>
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<td>1.315e+03</td>
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</table>

1.105e+03 7.700e+06 4.750e-05 smoothed data
1.142e+03 5.600e+06 4.750e-05
1.175e+03 4.150e+06 4.750e-05
1.210e+03 3.150e+06 4.750e-05
1.248e+03 2.470e+06 4.750e-05
1.290e+03 1.880e+06 4.750e-05
1.315e+03 1.620e+06 4.750e-05

Comments on Data
A graph of log yield strength vs. 1/T yield parallel straight lines which is in agreement with the dislocation theory.

Reference
PLASTIC DEFORMATION OF SILICON MONOCRystals OF DIFFERENT BASIC DISLOCATIONS DENSITY IN THE YIELD POINT REGION.
Doerschel, J. Kirsch, F. G.
Baehr, R.
KRIST. TECH.
12 (11), 1191-200, 1977.
Figure 164 Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

Composition

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7e13</td>
<td>cm^{-3}</td>
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<tr>
<td>1.0e16</td>
<td>cm^{-3}</td>
</tr>
<tr>
<td>8.0e15</td>
<td>cm^{-3}</td>
</tr>
</tbody>
</table>

Phosphorus Dopant Concentration
Carbon Concentration
Oxygen Concentration

Material Preparation

Crystal Growing Method:
Float-zone grown, n-type, grown-in dislocation density

Additional Preparation/Conditioning

Surface Treatment:
Chemically polished

Specimen Identification

Dimensions (Geometry):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
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<tr>
<td>Width</td>
<td>3. mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>3. mm</td>
</tr>
</tbody>
</table>

Orientation With Respect To Material: [123] Direction

Additional Identifiers:
Slip system along {111} planes and <101> directions

Additional Properties

Electrical Properties:
Electrical Resistivity: 250. \( \Omega \) cm
Temperature: 298. K

Other Properties-Numerical:
Dislocation Density: 6.5e04 \( \text{cm}^{-2} \)

Measurement/Evaluation Method

Name/Description:
Compression Loaded Bar Method
Testing machine not specified, probably Instron machine.
Resolved shear properties derived from measured stress-strain curves.

Parameters-Codified:
Pressure: 1.e-06 torr

Measured/Evaluated Properties

X: Temperature
Y: Shear Strength, Resolved, Lower Yield

K
Pa
Z1 : Shear Strain Rate, Resolved \( \text{s}^{-1} \)

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.105e+03</td>
<td>8.480e+06</td>
<td>1.450e-04</td>
<td>smoothed data</td>
</tr>
<tr>
<td>1.140e+03</td>
<td>6.430e+06</td>
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</tr>
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<td>1.248e+03</td>
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<td>1.450e-04</td>
<td></td>
</tr>
<tr>
<td>1.288e+03</td>
<td>2.430e+06</td>
<td>1.450e-04</td>
<td></td>
</tr>
<tr>
<td>1.315e+03</td>
<td>2.140e+06</td>
<td>1.450e-04</td>
<td></td>
</tr>
</tbody>
</table>

| 1.105e+03 | 5.560e+06 | 4.750e-05 | smoothed data     |
| 1.142e+03 | 4.220e+06 | 4.750e-05 |                    |
| 1.175e+03 | 3.360e+06 | 4.750e-05 |                    |
| 1.210e+03 | 2.720e+06 | 4.750e-05 |                    |
| 1.248e+03 | 2.170e+06 | 4.750e-05 |                    |
| 1.288e+03 | 1.730e+06 | 4.750e-05 |                    |
| 1.315e+03 | 1.520e+06 | 4.750e-05 |                    |

Comments on Data
Grown-in dislocation density lowers the yield strength as compared to dislocation-free crystals.
Log yield strength vs. 1/T gave parallel straight lines which is in agreement with the dislocation theory.

Reference
PLASTIC DEFORMATION OF SILICON MONOCRYSTALS OF DIFFERENT BASIC DISLOCATIONS DENSITY IN THE YIELD POINT REGION.
Doerschel, J. Kirsch, F. G.
Baehr, R.
KRIST. TECH.
12 (11), 1191-200, 1977.
Figure 165  Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

Composition
1.0e20 cm⁻³ Phosphorus Dopant Concentration

Vendor/Producer/Fabricator
Wacker Chemie, Munchen
Coating Description:
Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished
Specimens were cut with a diamond saw.

Specimen Identification
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Instron machine mounted to a high-temperature apparatus. Tests
carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).

Measured/Evaluated Properties
X : Temperature K
Y : Shear Strength, Resolved, Lower Yield Pa
Z1 : Shear Strain Rate, Resolved s⁻¹

Data Points:

<table>
<thead>
<tr>
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<th>Z1</th>
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</thead>
<tbody>
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<td>4.770e-03</td>
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<td>1.268e+03</td>
<td>1.170e+07</td>
<td>2.390e-03</td>
</tr>
</tbody>
</table>
1.370e+03  8.100e+06  2.390e-03
1.370e+03  7.600e+06  2.390e-04
1.316e+03  8.800e+06  2.390e-04
1.268e+03  9.500e+06  2.390e-04
1.268e+03  1.020e+07  2.390e-04
1.221e+03  1.060e+07  2.390e-04
1.172e+03  1.360e+07  2.390e-04
1.168e+03  1.280e+07  2.390e-04
1.119e+03  1.490e+07  2.390e-04
1.071e+03  1.770e+07  2.390e-04
1.071e+03  1.840e+07  2.390e-04

**Comments on Data**
A graph of log yield strength vs. 1/T yields straight lines of slopes different than the ones obtained for pure silicon.

**Reference**
THE INITIAL STAGE OF PLASTIC DEFORMATION OF SILICON HIGHLY DOPED WITH PHOSPHORUS.
Siethoff, H.
ACTA METALL.
17, 793-801, 1969.
Figure 166 Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

**Vendor/Producer/Fabricator**
Wacker Chemie, Munchen

**Material Preparation**
Crystal Growing Method:
Floating zone, p-type, dislocation-free

**Additional Preparation/Conditioning**
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

**Specimen Identification**
Dimensions (Geometry):
   Length 15. mm
   Width 3.4 mm
   Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
   Orientation suitable for single slip

**Measurement/Evaluation Method**
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N2, 8 percent H2) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.

**Measured/Evaluated Properties**
X : Phosphorus Dopant Concentration \( \text{m}^{-3} \)
Y : Shear Strength, Resolved, Lower Yield \( \text{Pa} \)
Z1 : Temperature \( \text{K} \)
Z2 : Shear Strain Rate, Resolved \( \text{s}^{-1} \)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.000e-02</td>
</tr>
<tr>
<td>5.100e+25</td>
<td>1.240e+07</td>
<td>1.373e+03</td>
<td>2.000e-02</td>
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<td>1.000e+26</td>
<td>1.350e+07</td>
<td>1.373e+03</td>
<td>2.000e-02</td>
</tr>
</tbody>
</table>
1.300e+26  1.400e+07  1.373e+03  2.000e-02

**Comments on Data**
Phosphorus-doping shows a weak increase in lower yield strength as compared to boron-doping

**Reference**
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 167 Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

******************************************************************************

**Composition**

1.0e20 cm\(^{-3}\) Phosphorus Dopant Concentration

**Vendor/Producer/Fabricator**

Wacker Chemie, Munchen
Coating Description:
Float-zone, p-type, dislocation free

**Additional Preparation/Conditioning**

Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished
Specimens were cut with a diamond saw.

**Specimen Identification**

Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction

**Measurement/Evaluation Method**

Name/Description:
Compression Loaded Bar Method
Instron machine mounted to a high-temperature apparatus. Tests
carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).

**Measured/Evaluated Properties**

X: Shear Strain Rate, Resolved s\(^{-1}\)
Y: Shear Strength, Resolved, Lower Yield Pa
Z1: Temperature K

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.500e-04</td>
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<td>1.173e+03</td>
</tr>
<tr>
<td>4.800e-04</td>
<td>1.310e+07</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>1.200e-03</td>
<td>1.350e+07</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>2.500e-03</td>
<td>1.720e+07</td>
<td>1.173e+03</td>
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<td>9.700e+06</td>
<td>1.273e+03</td>
</tr>
<tr>
<td>2.400e-04</td>
<td>1.030e+07</td>
<td>1.273e+03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>----------------</td>
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</tr>
<tr>
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<td>1.000e+07</td>
<td>1.273e+03</td>
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<tr>
<td>1.200e-03</td>
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**Comments on Data**
Lower yield strength of the heavily doped crystals showed marked deviations from that of pure and low doped crystals especially at low strain rates. Behavior interpreted as solid solution hardening due to electrostatic interaction between dislocations and solute atoms.

**Reference**
THE INITIAL STAGE OF PLASTIC DEFORMATION OF SILICON HIGHLY DOPED WITH PHOSPHORUS.
Siethoff, H.
ACTA METALL.
17, 793-801, 1969.
Figure 168  Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Lower Yield

Composition
1.e18 cm⁻³ Oxygen Concentration
2.e16 cm⁻³ Carbon Concentration

Vendor/Producer/Fabricator
KOFU Works of Hitachi Ltd.

Material Preparation
Crystal Growing Method:
Czochralski grown, dislocation free, n-type
Grown with diameter of 76 mm in the [111] direction.
Descriptors-Textual:
Annealed at 1323. K for various times.

Additional Preparation/Conditioning
Surface Treatment:
Surface layers polished and removed to depth more than
250 microns.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity
Temperature 7-9 Ω cm
298 K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Test conducted in vacuum using Instrom machine mounted to high
temperature apparatus. Resolved shear properties derived from
measured data.
Parameters-Codified:
Pressure: 1.e-05 Torr
Shear Strain, Resolved: 1.1e-04 s⁻¹
Temperature: 1173. K
Annealing Temperature: 1323. K

Measured/Evaluated Properties
X : Annealing Time s
Y : Shear Strength, Resolved, Lower Yield  
Z1 : Annealing Temperature  
Z2 : Temperature  
Z3 : Shear Strain Rate, Resolved

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</table>

Comments on Data

Yield strength decreased drastically with annealing time in the range of 0 to 10 hours; longer annealing time did not significantly reduce yield strength.

Reference

MECHANICAL BEHAVIOR OF CZOCHRALSki-SILICON CRYSTALS AS AFFECTED BY PRECIPITATION AND DISSOLUTION OF OXYGEN ATOMS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS.
Figure 169 Shear Strength, Resolved, Lower Yield of Silicon: P doped
MATERIAL: Silicon, n-type
PROPERTY: Shear Strength, Resolved, Lower Yield

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
  Float-zone technique
  Crystal grown in a high purity argon gas atmosphere.
Descriptors-Textual:
  Dislocation density controlled by deformation at 1173 K and various strains (less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity: 460. Ω cm
  Temperature: 298. K
Other Properties-Numerical:
  Dislocation Density: 2.0e04 cm⁻²
  Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
  Shear Response Under Tensile Loading
Parameters-Textual:
  Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of luders bands occurred.
Parameters-Codified:
  Pressure: 1.3e-02 Pa

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
  Pressure: 1.e-04 torr

Measured/Evaluated Properties
  X: Temperature K
  Y: Shear Strength, Resolved, Lower Yield Pa
Z1 : Shear Strain Rate, Resolved \( s^{-1} \)

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Comments on Data
A graph of log yield strength vs. 1/T gave straight lines with an activation energy of 0.8 eV.

Reference
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I. Sumino, K.
PHYS. STATUS SOLIDI A
Figure 170 Shear Strength, Resolved, Lower Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Lower Yield

HTMIAC/CINDAS 1994
PURDUE UNIVERSITY
DATA SET 171

Vendor/Producer/Fabricator
Wacker

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
{111} and {541} side faces cut with a diamond saw and
diamond polished (1/4 micron)

Specimen Identification
Dimensions (Geometry):
  Length 14. mm
  Thickness 4.25 mm
  Width 4.25 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Specimen oriented to obtain a single slip deformation
along {111} planes and <101> directions

Additional Properties
Electrical Properties:
  Electrical Resistivity >5. \(\Omega\) cm
  Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature compression stage apparatus mounted on an
Instron machine. A continuous flow of forming gas (10 pct. H(2),
90 pct. N(2)) maintained during each test. Curves of resolved
shear stress - strain derived from the recorded data.

Measured/Evaluated Properties
X : Temperature K
Y : Shear Strength, Resolved, Lower Yield Pa
ZI : Shear Strain Rate, Resolved s\(^{-1}\)

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Comments on Data
At the lower strain rate, the temperature dependence consists of three stages. The low-temperature range in which the yield strength decreases rapidly with increasing temperature followed from about 1170 - 1320 K by a plateau where it remains constant or even slightly increases with temperature. At higher temperatures the flow stress extrapolated from stage I of easy glide decreases again. At higher strain rate the plateau no longer appears.

Reference
ON THE YIELD POINT OF FLOATING-ZONE SILICON SINGLE CRYSTALS. I. YIELD STRESSES AND ACTIVATION PARAMETERS.
Omri, M. Tete, C. Michel, J. P.
George, A.
PHILOS. MAG. A
Figure 171 Shear Strength, Resolved, Lower Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Lower Yield

Vendor/Producer/Fabricator
Wacker

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free
Descriptors-Textual:
crystal pre-strained to extend temperature range towards
lower range

Additional Preparation/Conditioning
Surface Treatment:
\{111\} and \{541\} side faces cut with a diamond saw and
diamond polished (1/4 micron)

Specimen Identification
Dimensions (Geometry):
Length: 14. mm
Thickness: 4.25 mm
Width: 4.25 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Specimen oriented to obtain a single slip deformation
along \{111\} planes and <101> directions

Additional Properties
Electrical Properties:
Electrical Resistivity: >5. Ω cm
Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature compression stage apparatus mounted on an
Instron machine. A continuous flow of forming gas (10 pct. H(2),
90 pct. N(2)) maintained during each test. Curves of resolved
shear stress - strain derived from the recorded data.
Parameters-Codified:
Pre-Strain Rate, Plastic: 7.e-02 pct. (shear)
Shear Strain Rate, Resolved: 2.e-05 s[-1] (pre-straining)
Pre-Strain Temperature: 1323. K
**Measured/Evaluated Properties**

X : Temperature \[\text{K}\]
Y : Shear Strength, Resolved, Lower Yield \[\text{Pa}\]
Z1 : Shear Strain Rate, Resolved \[\text{s}^{-1}\]

**Data Points**:

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**Comments on Data**

Lower yield strength of pre-strained crystals did not exhibit the same plateau observed for the as-received crystals at all temperatures.

Pre-straining conditions (2.e-05 s[-1] at 1323 K) chosen to create as many mobile dislocations as possible but at the same time keep hardening as low as possible.
Reference

ON THE YIELD POINT OF FLOATING-ZONE SILICON SINGLE CRYSTALS. I. YIELD STRESSES AND ACTIVATION PARAMETERS.
Omri, M. Tete, C. Michel, J. P.
George, A.
PHILOS. MAG. A
Figure 172 Shear Strength, Resolved, Lower Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Lower Yield

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
  Float-zone technique
  Crystal grown in a high purity argon gas atmosphere.
Descriptors-Textual:
  Dislocation density controlled by deformation at 1173 K and various strains( less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity: 460. Ω cm
  Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
  Shear Response Under Tensile Loading
Parameters-Textual:
  Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of luders bands occurred.
Parameters-Codified:
  Pressure: 1.3e-02 Pa

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
  Pressure: 1.e-04 torr

Measured/Evaluated Properties
  X: Dislocation Density
  Y: Shear Strength, Resolved, Lower Yield
  Z1: Temperature
  Z2: Shear Strain Rate, Resolved
Data Points:

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<td>4.500e+10</td>
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<tr>
<td>3.700e+09</td>
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<td>1.200e-04</td>
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<tr>
<td>1.300e+10</td>
<td>3.700e+06</td>
<td>1.173e+03</td>
<td>1.200e-04</td>
</tr>
</tbody>
</table>

Comments on Data:
Dislocation density determined by etch-pit technique.
Lower yield strength, unlike upper yield, does not seem to be affected by dislocation density.

Reference:
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I. Sumino, K.
PHYS. STATUS SOLIDI A
Figure 173 Shear Strength, Resolved, Lower Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Lower Yield

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
Float-zone technique
Crystal grown in a high purity argon gas atmosphere.

Descriptors-Textual:
Dislocation density controlled by deformation at 1173 K and various strains (less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 460. Ω cm
Temperature 298. K

Other Properties-Numerical:
Dislocation Density 2.0e04 cm⁻²

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading

Parameters-Textual:
Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of luders bands occurred.

Parameters-Codified:
Pressure: 1.3e-02 Pa

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Descriptors-Numerical:
Pressure 1.e-04 torr

Measured/Evaluated Properties
X: Shear Strain Rate, Resolved s⁻¹
Y: Shear Strength, Resolved, Lower Yield Pa
Z1: Temperature K
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.400e-05</td>
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<td>1.073e+03</td>
</tr>
<tr>
<td>5.800e-05</td>
<td>1.080e+07</td>
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<td>6.100e-05</td>
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<tr>
<td>5.800e-04</td>
<td>6.300e+06</td>
<td>1.273e+03</td>
</tr>
</tbody>
</table>

Comments on Data
Yield strength increases with increasing strain rate.

Reference
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I. Sumino, K.
PHYS. STATUS SOLIDI A
Figure 174 Shear Strength, Resolved, Lower Yield of Silicon, n-type
Material Preparation
   Crystal Growing Method:
      Float-zone with grown-in dislocation density

Additional Preparation/Conditioning
   Surface Treatment:
      Specimens were cut with a diamond saw, lapped with diamond paste and chemically polished.

Specimen Identification
   Dimensions (Geometry):
      Length: 15. mm
      Width: 3.4 mm
      Thickness: 3.4 mm
   Orientation With Respect To Material: [123] Direction

Additional Properties
   Electrical Properties:
      Electrical Resistivity: 200.-1000. $\Omega$ cm
      Temperature: 298. K
   Other Properties-Numerical:
      Dislocation Density: 1.e+04 cm$^{-2}$
      Temperature: 298. K

Measurement/Evaluation Method
   Name/Description:
      Shear Response Under Compressive Loading
   Parameters-Textual:
      Deformation carried out under an atmosphere of forming gas (92% N2, 8% H2) or argon in Instron machine using high-temperature compression apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
   X: Temperature $K$
   Y: Shear Strength, Resolved, Lower Yield $Pa$
   Z1: Shear Strain Rate, Resolved $s^{-1}$

Data Points:

   X  Y  Z1

595
1.575e+03  3.200e+06  5.000e-03
1.376e+03  6.400e+06  5.000e-03
1.273e+03  1.070e+07  5.000e-03
1.176e+03  2.060e+07  5.000e-03

1.573e+03  1.400e+06  4.800e-02
1.373e+03  2.900e+06  4.800e-02
1.275e+03  4.700e+06  4.800e-02
1.222e+03  6.000e+06  4.800e-02
1.171e+03  9.100e+06  4.800e-02
1.121e+03  1.300e+07  4.800e-02
1.073e+03  1.850e+07  4.800e-02
1.023e+03  3.080e+07  4.800e-02

Comments on Data
Data was digitized from figure 2
Lower yield behavior of silicon at temperatures between 873 K and
the melting point are compatible with results from other authors
with dependencies predicted by Haasen’s model.

Reference
YIELD POINT AND DISLOCATION MOBILITY IN SILICON AND
GERMANIUM.
Schroeter, W. Brion, H. G.
Siethoff, H.
J. APPL. PHYS.
54 (4), 1816-20, 1983.
Figure 175 Shear Strength, Resolved, Lower Yield of Silicon, p-type
MATERIAL: Silicon, p-type

PROPERTY: Shear Strength, Resolved, Lower Yield

Material Preparation
Crystal Growing Method:
Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):

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<thead>
<tr>
<th></th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
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<tr>
<td>Thickness</td>
<td>3.4</td>
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</table>

Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:

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<tr>
<th>Property</th>
<th>Value</th>
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</thead>
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<tr>
<td>Electrical Resistivity</td>
<td>200-1200 Ω cm</td>
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<tr>
<td>Temperature</td>
<td>298. K</td>
</tr>
</tbody>
</table>

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
High-temperature apparatus mounted to Instron machine. Tests carried under an atmosphere of forming gas (92 pct N2, 8 pct H2). Resolved shear properties derived from measured stress-strain curves.

Measured/Evaluated Properties

<table>
<thead>
<tr>
<th>X: Temperature</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: Shear Strength, Resolved, Lower Yield</td>
<td>Pa</td>
</tr>
<tr>
<td>Z1: Shear Strain Rate, Resolved</td>
<td>s⁻¹</td>
</tr>
</tbody>
</table>

Data Points:

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>1.370e+03</td>
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<tr>
<td>1.272e+03</td>
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<td>1.119e+03</td>
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598
1.070e+03  1.790e+07  4.770e-04
9.790e+02  3.000e+07  4.770e-04
1.370e+03  2.200e+06  2.390e-04
1.272e+03  3.600e+06  2.390e-04
1.225e+03  4.900e+06  2.390e-04
1.169e+03  6.800e+06  2.390e-04
1.119e+03  9.800e+06  2.390e-04
1.070e+03  1.420e+07  2.390e-04

Comments on Data
Observed results for pure silicon were analyzed by means of dislocation theory. Dislocations move in viscous flow with an activation energy of 2.3 eV.

Reference
THE YIELD POINT OF SILICON AND SILICON-GERMANIUM SOLID SOLUTIONS.
Siethoff, H.
MATER. SCI. ENG.
Figure 176 Shear Strength, Resolved, Lower Yield of Silicon, p-type
Material Preparation
Crystal Growing Method:
Float-zone with grown-in dislocation density

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw, lapped with diamond paste and chemically polished.

Specimen Identification
Dimensions (Geometry):
Length: 15. mm
Width: 3.4 mm
Thickness: 3.4 mm
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity: 200.-1000. Ω cm
Temperature: 298. K
Other Properties-Numerical:
Dislocation Density: 1.e+04 cm\(^{-2}\)
Temperature: 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading
Parameters-Textual:
Deformation carried out under an atmosphere of forming gas (92% N\(_2\), 8% H\(_2\)) or argon in Instron machine using high-temperature compression apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
X: Shear Strain Rate, Resolved s\(^{-1}\)
Y: Shear Strength, Resolved, Lower Yield Pa
Z1: Temperature K

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
</table>

601
<p>| | | |</p>
<table>
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<tr>
<td>8.090e-03</td>
<td>3.200e+06</td>
<td>1.573e+03</td>
</tr>
</tbody>
</table>

**Comments on Data**

Data was digitized from figure 1
Lower yield stress as a function of strain rate at different temperatures in log-log scale give straight parallel lines.

**Reference**

YIELD POINT AND DISLOCATION MOBILITY IN SILICON AND GERMANIUM.
Schroeter, W. Brion, H. G.
Siethoff, H.
J. APPL. PHYS.
54 (4), 1816-20, 1983.
Figure 177  Shear Strength, Resolved, Lower Yield of Silicon, p-type
MATERIAL:  Silicon, p-type

PROPERTY:  Shear Strength, Resolved, Lower Yield

****************************

Material Preparation
Crystal Growing Method:
  Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
  Length  15. mm
  Width   3.4 mm
  Thickness  3.4 mm
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity  200-1200 $\Omega$ cm
  Temperature  298. K

Measurement/Evaluation Method
Name/Description:
  Shear Response Under Compressive Loading
  High-temperature apparatus mounted to Instron machine. Tests
carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).
  Resolved shear properties derived from measured stress-strain
curves.

Measured/Evaluated Properties
X : Shear Strain Rate, Resolved
Y : Shear Strength, Resolved, Lower Yield
Z1 : Temperature

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.400e-04</td>
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<td>5.500e-04</td>
<td>4.800e+06</td>
<td>1.273e+03</td>
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<td>1.200e-03</td>
<td>6.600e+06</td>
<td>1.273e+03</td>
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<tr>
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<td>8.200e+06</td>
<td>1.273e+03</td>
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<tr>
<td>4.600e-03</td>
<td>1.100e+07</td>
<td>1.273e+03</td>
</tr>
</tbody>
</table>
1.400e-02  1.520e+07  1.273e+03
1.200e-04  5.300e+06  1.173e+03
2.400e-04  7.400e+06  1.173e+03
4.800e-04  9.200e+06  1.173e+03
1.200e-03  1.270e+07  1.173e+03
2.500e-03  1.640e+07  1.173e+03
4.900e-03  2.030e+07  1.173e+03
1.200e-02  2.820e+07  1.173e+03

Comments on Data
Observed results for pure silicon were analyzed by means of dislocation theory. Dislocations move in viscous flow with an activation energy of 2.3 eV.

Reference
THE YIELD POINT OF SILICON AND SILICON-GERMANIUM SOLID SOLUTIONS.
Siethoff, H.
MATER. SCI. ENG.
Figure 178  Shear Strength, Resolved, Lower Yield of Silicon, p-type
MATERIAL: Silicon: B doped

PROPERTY: Shear Strength, Resolved, Upper Yield

******************************************************************************

**Composition**
1.25e20 cm\(^{-3}\)
Boron Dopant Concentration

**Vendor/Producer/Fabricator**
Wacker Chemie, Munchen

**Material Preparation**
Crystal Growing Method:
Floating zone, p-type, dislocation-free

**Additional Preparation/Conditioning**
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

**Specimen Identification**
Dimensions (Geometry):
- Length: 15. mm
- Width: 3.4 mm
- Thickness: 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

**Measurement/Evaluation Method**
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N\(_2\), 8 percent H\(_2\)) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.

**Measured/Evaluated Properties**
X : Shear Strain Rate, Resolved
Y : Shear Strength, Resolved, Upper Yield
Z1 : Temperature

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
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<tbody>
<tr>
<td>4.800e-05</td>
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</table>
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2.400e-04  2.660e+07  1.173e+03
4.900e-04  3.480e+07  1.173e+03
1.100e-03  5.120e+07  1.173e+03
2.500e-03  6.450e+07  1.173e+03
1.200e-04  1.010e+07  1.373e+03
2.400e-04  1.270e+07  1.373e+03
4.900e-04  1.220e+07  1.373e+03
1.200e-03  1.660e+07  1.373e+03
2.400e-03  1.790e+07  1.373e+03
5.200e-03  2.740e+07  1.373e+03
1.200e-02  4.030e+07  1.373e+03

Comments on Data
Data was digitized from Figure 1.
At high strain rates the slope of curves is the same for pure
and doped Silicon. The stress exponent of dislocation velocity
remains unchanged by doping in this region. At low strain rates
the yield point, especially lower yield, is independent of strain
rate.

Reference
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT
OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 179 Shear Strength, Resolved, Upper Yield of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Shear Strength, Resolved, Upper Yield

Composition
4.0e19 cm^{-3} Boron Dopant Concentration

Vendor/Producer/Fabricator
Wacker Chemie, Munchen

Material Preparation
Crystal Growing Method:
Floating zone, p-type, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N2, 8 percent H2) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.

Measured/Evaluated Properties
X : Shear Strain Rate, Resolved s^{-1}
Y : Shear Strength, Resolved, Upper Yield Pa
Z1 : Temperature K

Data Points:

<table>
<thead>
<tr>
<th>X</th>
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<td>$1.373e+03$</td>
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</tbody>
</table>

**Comments on Data**
Data was digitized from Figure 2.
At high strain rates the slope of curves is the same for pure
and doped Silicon. The stress exponent of dislocation velocity
remains unchanged by doping in this region.

**Reference**
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT
OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
Figure 180  Shear Strength, Resolved, Upper Yield of Silicon: B doped
MATERIAL: Silicon: C doped

PROPERTY: Shear Strength, Resolved, Upper Yield

Composition
6.0e17 cm\(^{-3}\) Oxygen Concentration

Vendor/Producer/Fabricator
Sony Corp. and Komatsu Electronic Metals Co.

Material Preparation
Crystal Growing Method:
Czochralski grown
Descriptors-Textual:
Prior to tensile tests all specimens were subjected to annealing
at 1573 K for 2 hours followed by rapid cooling at a rate of 150 C
per minute to eliminate possible segregation of carbon and/or
oxygen, and also to homogenize the distribution of defects.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Other Properties-Numerical:
Dislocation Density 1.0e06 cm\(^{-2}\)

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tests conducted in vacuum using an Instron machine.
Dislocation density determined by etch-pit technique.
Resolved shear properties derived from recorded data.
Carbon and oxygen concentrations determined by IR absorption.
Parameters-Codified:
Shear Strain Rate, Resolved: 1.1e-04 s[-1]
Pressure: 1.33e-02 pa

Measured/Evaluated Properties
X: Carbon Concentration m\(^{-3}\)
Y: Shear Strength, Resolved, Upper Yield Pa
Z1: Temperature K

Data Points:

X Y Z1

613
<p>| | | |</p>
<table>
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<tr>
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</table>

**Comments on Data**

Carbon results in an increase in mechanical strength of silicon crystals if it coexists with oxygen concentrations higher than 5.0e17 atoms/cm³. Upper yield stress increases monotonically with increase in carbon concentration.

**Reference**

**ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.**

Yonenaga, I. Sumino, K.

JP. J. APPL. PHYS., PART 2

23 (8), 590-2, 1984.
Figure 181 Shear Strength, Resolved, Upper Yield of Silicon: C doped
MATERIAL: Silicon: C doped

PROPERTY: Shear Strength, Resolved, Upper Yield

**Composition**

<table>
<thead>
<tr>
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<th>Unit</th>
<th>Description</th>
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</thead>
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<td>Carbon Concentration</td>
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<tr>
<td>1.5e17</td>
<td>cm$^{-3}$</td>
<td>Oxygen Concentration</td>
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**Vendor/Producer/Fabricator**
Sony Corp. and Komatsu Electronic Metals Co.

**Material Preparation**
Crystal Growing Method:
- Float-zone grown

Descriptors-Textual:
- Prior to tensile tests all specimens were subjected to annealing at 1573 K for 2 hours followed by rapid cooling at a rate of 150 C per minute to eliminate possible segregation of carbon and/or oxygen, and also to homogenize the distribution of defects.

**Specimen Identification**
Orientation With Respect To Material: [123] Direction

**Measurement/Evaluation Method**
Name/Description:
- Shear Response Under Tensile Loading
- Tests conducted in vacuum using an Instron machine.
- Dislocation density determined by etch-pit technique.
- Resolved shear properties derived from recorded data.
- Carbon and oxygen concentrations determined by IR absorption.

Parameters-Codified:
- Shear Strain Rate, Resolved: 1.1e-04 s$^{-1}$
- Pressure: 1.33e-02 Pa

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
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Data Points:
\[ \begin{array}{ccc}
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8.200e+07 & 1.460e+07 & 1.173e+03 \\
3.900e+08 & 9.900e+06 & 1.173e+03 \\
1.300e+10 & 3.800e+06 & 1.173e+03 \\
\end{array} \]

Comments on Data
The upper yield strength increases with a decrease in dislocation density. At 1073 K effect is more profound as compared to 1173 K. Results show that carbon atoms dissolved in a silicon crystal have little effect in locking dislocations by themselves without the presence of oxygen atoms.

Reference
ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS., PART 2
23 (8), 590-2, 1984.
Figure 182 Shear Strength, Resolved, Upper Yield of Silicon: C doped
MATERIAL: Silicon: O doped

PROPERTY: Shear Strength, Resolved, Upper Yield

Composition
1.5e17 cm⁻³ Oxygen Concentration

Vendor/Producer/Fabricator
Sony Corp. and Komatsu Electronic Metals Co.

Material Preparation
Crystal Growing Method:
Float-zone grown
Descriptors-Textual:
Prior to tensile tests all specimens were subjected to annealing at 1573 K for 2 hours followed by rapid cooling at a rate of 150°C per minute to eliminate possible segregation of carbon and/or oxygen, and also to homogenize the distribution of defects.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tests conducted in vacuum using an Instron machine.
Dislocation density determined by etch-pit technique.
Resolved shear properties derived from recorded data.
Carbon and oxygen concentrations determined by IR absorption.
Parameters-Codified:
Shear Strain Rate, Resolved: 1.1e-04 s⁻¹
Pressure: 1.33e-02 pa

Measured/Evaluated Properties
X: Dislocation Density m⁻²
Y: Shear Strength, Resolved, Upper Yield Pa
Z1: Temperature K

Data Points:

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<th>Z1</th>
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1.000e+10   1.070e+07   1.073e+03
1.700e+10   8.800e+06   1.073e+03
2.000e+10   1.070e+07   1.073e+03
1.600e+08   9.000e+06   1.173e+03
2.000e+08   1.050e+07   1.173e+03
1.700e+09   5.000e+06   1.173e+03
3.600e+09   4.600e+06   1.173e+03
1.300e+10   3.400e+06   1.173e+03
1.700e+10   3.800e+06   1.173e+03

Comments on Data
Results show that mobility of dislocations in a silicon crystal does not appear to be influenced by oxygen atoms. Magnitude of yield strength of carbon-doped differs very little from oxygen-doped.

Reference
ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS., PART 2
23 (8), 590-2, 1984.
Figure 183 Shear Strength, Resolved, Upper Yield of Silicon: O doped
MATERIAL:  Silicon: O doped

PROPERTY:  Shear Strength, Resolved, Upper Yield

Composition
1.5e17  cm\(^{-3}\)  Oxygen Concentration

Vendor/Producer/Fabricator
Sony Corp. and Komatsu Electronic Metals Co.

Material Preparation
Crystal Growing Method:
Czochralski grown
Descriptors-Textual:
Prior to tensile tests all specimens were subjected to annealing at 1573 K for 2 hours followed by rapid cooling at a rate of 150°C per minute to eliminate possible segregation of carbon and/or oxygen, and also to homogenize the distribution of defects.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tests conducted in vacuum using an Instron machine.
Dislocation density determined by etch-pit technique.
Resolved shear properties derived from recorded data.
Carbon and oxygen concentrations determined by IR absorption.
Parameters-Codified:
Shear Strain Rate, Resolved: 1.1e-04 s\([-1]\]
Pressure: 1.33e-02 pa

Measured/Evaluated Properties
X:  Dislocation Density  \(m^{-2}\)
Y:  Shear Strength, Resolved, Upper Yield  \(Pa\)
Z1:  Temperature  \(K\)

Data Points:

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8.000e+08  1.250e+07  1.173e+03
3.000e+09  8.500e+06  1.173e+03
1.200e+10  5.300e+06  1.173e+03

Comments on Data
Upper yield strength of Czochralski grown silicon is much higher than those of float zone both undoped and doped with carbon.

Reference
ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS., PART 2
23 (8), 590-2, 1984.
Figure 184 Shear Strength, Resolved, Upper Yield of Silicon: 0 doped
MATERIAL: Silicon: O doped

PROPERTY: Shear Strength, Resolved, Upper Yield

**********

Vendor/Producer/Fabricator
Sony Corp. and Komatsu Electronic Metals Co.

Material Preparation
Crystal Growing Method:
Czochralski grown
Descriptors-Textual:
Prior to tensile tests all specimens were subjected to annealing
at 1573 K for 2 hours followed by rapid cooling at a rate of 150 C
per minute to eliminate possible segregation of carbon and/or
oxygen, and also to homogenize the distribution of defects.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Other Properties-Numerical:
Dislocation Density 1.0e06 cm⁻²

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tests conducted in vacuum using an Instron machine.
Dislocation density determined by etch-pit technique.
Resolved shear properties derived from recorded data.
Carbon and oxygen concentrations determined by IR absorption.
Parameters-Codified:
Shear Strain Rate, Resolved: 1.1e-04 s[-1]
Pressure: 1.33e-02 pa

Measured/Evaluated Properties
X : Oxygen Concentration m⁻³
Y : Shear Strength, Resolved, Upper Yield Pa
Z1 : Temperature K
Z2 : Carbon Concentration m⁻³

Data Points:

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<td>1.173e+03</td>
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</table>

**Comments on Data**
Carbon content has no effect on dislocation-free crystal.
Upper yield strength increases distinctly by presence of carbon if crystal contains oxygen at concentration above 5.0e17 atoms/cm[3]. Carbon content has almost no influence on upper yield strength when oxygen content is below 4.0e17 atoms/cm[3].

**Reference**
ROLE OF CARBON IN THE STRENGTHENING OF SILICON CRYSTALS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS., PART 2
23 (8), 590-2, 1984.
Figure 185 Shear Strength, Resolved, Upper Yield of Silicon: O doped
**MATERIAL:** Silicon: P doped

**PROPERTY:** Shear Strength, Resolved, Upper Yield

**Vendor/Producer/Fabricator**
Wacker Chemie, Munchen

**Material Preparation**
Crystal Growing Method:
Floating zone, p-type, dislocation-free

**Additional Preparation/Conditioning**
Surface Treatment:
Specimens were cut with a diamond saw,
lapped with diamond paste and chemically polished

**Specimen Identification**
Dimensions (Geometry):
Length 15. mm
Width 3.4 mm
Thickness 3.4 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Orientation suitable for single slip

**Measurement/Evaluation Method**
Name/Description:
Compression Loaded Bar Method
Deformation carried out at constant strain rates under an
atmosphere of forming gas (92 percent N2, 8 percent H2) or
argon in Instron machine using high temperature compression
apparatus. Accuracy of temperature measurement was +/- 1 K.
Parameters-Codified:
Shear Strain Rate, Resolved: 4.8e-03 s[-1]

**Measured/Evaluated Properties**
X : Temperature K
Y : Shear Strength, Resolved, Upper Yield Pa
Z1 : Phosphorus Dopant Concentration m^3

Data Points:

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<tr>
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628
1.273e+03    3.640e+07    5.000e+25  
1.224e+03    4.860e+07    5.000e+25  
1.175e+03    7.010e+07    5.000e+25  

**Comments on Data**
Activation energy for P-doped Silicon was found to be 2.0 eV as compared to 2.3 eV for pure Silicon.

**Reference**
THE EFFECT OF CHARGED IMPURITIES ON THE YIELD POINT OF SILICON.
Siethoff, H.
PHYS. STATUS SOLIDI
MATERIAL: Silicon: P doped
PROPERTY: Shear Strength, Resolved, Upper Yield

 Composition
  2.5e14 cm⁻³ Phosphorus Dopant Concentration
  1.0e16 cm⁻³ Carbon Concentration
  1.3e16 cm⁻³ Oxygen Concentration

 Material Preparation
  Crystal Growing Method:
    Float-zone grown, n-type, dislocation-free

 Additional Preparation/Conditioning
  Surface Treatment:
    Chemically polished

 Specimen Identification
  Dimensions (Geometry):
    Length 15. mm
    Width 3. mm
    Thickness 3. mm
  Orientation With Respect To Material: [123] Direction
  Additional Identifiers:
    Slip system along {111} planes and <101> directions

 Additional Properties
  Electrical Properties:
    Electrical Resistivity 16. Ω cm
    Temperature 298. K

 Measurement/Evaluation Method
  Name/Description:
    Compression Loaded Bar Method
    Testing machine not specified, probably Instron machine.
    Resolved shear properties derived from measured stress-strain curves.
  Parameters-Codified:
    Pressure: 1.e-06 torr

 Measured/Evaluated Properties
  X: Temperature K
  Y: Shear Strength, Resolved, Upper Yield Pa
  Z1: Shear Strain Rate, Resolved s⁻¹
Data Points:

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Comments on Data
A graph of log yield strength vs. 1/T yield parallel straight lines which is in agreement with the dislocation theory.

Reference
PLASTIC DEFORMATION OF SILICON MONOCRYSTALS OF DIFFERENT BASIC DISLOCATIONS DENSITY IN THE YIELD POINT REGION.
Doerschel, J. Kirscht, F. G.
Baehr, R.
KRIST. TECH.
12 (11), 1191-200, 1977.
Figure 187  Shear Strength, Resolved, Upper Yield of Silicon: P doped
MATERIAL: Silicon: P doped  HTMIAC/CINDAS 1994
PROPERTY: Shear Strength, Resolved, Upper Yield  PURDUE UNIVERSITY
DATA SET  188

Composition
1.7e13  cm⁻³  Phosphorus Dopant Concentration
1.0e16  cm⁻³  Carbon Concentration
8.0e15  cm⁻³  Oxygen Concentration

Material Preparation
Crystal Growing Method:
  Float-zone grown, n-type, grown-in dislocation density

Additional Preparation/Conditioning
Surface Treatment:
  Chemically polished

Specimen Identification
Dimensions (Geometry):
  Length  15.  mm
  Width  3.  mm
  Thickness  3.  mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
  Slip system along {111} planes and <101> directions

Additional Properties
Electrical Properties:
  Electrical Resistivity  250.  Ω cm
  Temperature  298.  K
Other Properties-Numerical:
  Dislocation Density  6.5e04  cm⁻²

Measurement/Evaluation Method
Name/Description:
  Compression Loaded Bar Method
Testing machine not specified, probably Instron machine.
Resolved shear properties derived from measured stress-strain curves.
Parameters-Codified:
  Pressure: 1.e-06 torr

Measured/Evaluated Properties
  X : Temperature  K
  Y : Shear Strength, Resolved, Upper Yield  Pa
Z1 : Shear Strain Rate, Resolved

Data Points :

<table>
<thead>
<tr>
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<th>Y</th>
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<th>Remarks:</th>
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<td>4.750e-05</td>
<td></td>
</tr>
<tr>
<td>1.287e+03</td>
<td>2.120e+06</td>
<td>4.750e-05</td>
<td></td>
</tr>
<tr>
<td>1.315e+03</td>
<td>1.810e+06</td>
<td>4.750e-05</td>
<td></td>
</tr>
</tbody>
</table>

Comments on Data

Grown-in dislocation density lowers the yield strength as compared to dislocation-free crystals.
Log yield strength vs. 1/T gave parallel straight lines which is in agreement with the dislocation theory.

Reference

PLASTIC DEFORMATION OF SILICON MONOCRystals OF DIFFERENT BASIC DISLOCATIONS DENSITY IN THE YIELD POINT REGION.
Doerschel, J. Kirsch, F. G.
Baehr, R.
KRIST. TECH.
12 ( 11 ), 1191-200, 1977.
Figure 188  Shear Strength, Resolved, Upper Yield of Silicon: P doped
MATERIAL: Silicon: P doped
PROPERTY: Shear Strength, Resolved, Upper Yield

Composition

1.0e20 \text{ cm}^{-3} \quad \text{Phosphorus Dopant Concentration}

Vendor/Producer/Fabricator

Wacker Chemie, Munchen
Coating Description:
Float-zone, p-type, dislocation free

Additional Preparation/Conditioning

Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished
Specimens were cut with a diamond saw.

Specimen Identification

Dimensions (Geometry):

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Width</td>
<td>Thickness</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>mm</td>
</tr>
</tbody>
</table>

Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method

Name/Description:
Compression Loaded Bar Method
Instron machine mounted to a high-temperature apparatus. Tests
carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).

Measured/Evaluated Properties

<table>
<thead>
<tr>
<th>X : Temperature</th>
<th>Y : Shear Strength, Resolved, Upper Yield</th>
<th>Z1 : Shear Strain Rate, Resolved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.370e+03</td>
<td>2.060e+07</td>
<td>4.770e-03</td>
</tr>
<tr>
<td>1.318e+03</td>
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<tr>
<td>1.265e+03</td>
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<tr>
<td>1.218e+03</td>
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<td>4.770e-03</td>
</tr>
<tr>
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<td>1.670e+07</td>
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<tr>
<td>1.267e+03</td>
<td>2.730e+07</td>
<td>2.390e-03</td>
</tr>
</tbody>
</table>
\begin{verbatim}
1.167e+03   4.230e+07   2.390e-03
1.369e+03   9.700e+06   4.770e-04
1.320e+03   1.190e+07   4.770e-04
1.269e+03   1.410e+07   4.770e-04
1.222e+03   1.940e+07   4.770e-04
1.169e+03   2.310e+07   4.770e-04
1.118e+03   2.800e+07   4.770e-04
1.070e+03   3.930e+07   4.770e-04
1.018e+03   5.630e+07   4.770e-04
1.369e+03   8.300e+06   2.390e-04
1.269e+03   1.260e+07   2.390e-04
1.169e+03   1.920e+07   2.390e-04
1.070e+03   3.190e+07   2.390e-04
\end{verbatim}

**Comments on Data**
A graph of log yield strength vs. 1/T yields straight lines of slopes different than the ones obtained for pure silicon.

**Reference**
THE INITIAL STAGE OF PLASTIC DEFORMATION OF SILICON HIGHLY DOPED WITH PHOSPHORUS.
Siethoff, H.
ACTA METALL.
17, 793-801, 1969.
Figure 189 Shear Strength, Resolved, Upper Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Upper Yield

Composition
1.0e20 cm\(^{-3}\) Phosphorus Dopant Concentration

Vendor/Producer/Fabricator
Wacker Chemie, Munchen
Coating Description:
Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished
Specimens were cut with a diamond saw.

Specimen Identification
Dimensions (Geometry):

<table>
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<tr>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
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</thead>
<tbody>
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<td>15. mm</td>
<td>3.4 mm</td>
<td>3.4 mm</td>
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</tbody>
</table>

Orientation With Respect To Material: [123] Direction

Measurement/Evaluation Method
Name/Description:
Compression Loaded Bar Method
Instron machine mounted to a high-temperature apparatus. Tests
carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).

Measured/Evaluated Properties

| X : Shear Strain Rate, Resolved | s\(^{-1}\) |
| Y : Shear Strength, Resolved, Upper Yield | Pa |
| Z1 : Temperature                | K      |

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.500e-04</td>
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<td>1.173e+03</td>
</tr>
<tr>
<td>4.900e-04</td>
<td>2.370e+07</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>1.300e-03</td>
<td>3.330e+07</td>
<td>1.173e+03</td>
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<td>2.500e-03</td>
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<td>2.500e-04</td>
<td>1.240e+07</td>
<td>1.273e+03</td>
</tr>
</tbody>
</table>

640
4.900e-04  1.450e+07  
1.300e-03  1.860e+07  
2.600e-03  2.690e+07  
4.900e-03  3.230e+07  
1.200e-02  4.970e+07  
2.500e-02  6.370e+07  
2.500e-04  8.600e+06  1.373e+03  
4.900e-04  9.400e+06  
2.400e-03  1.640e+07  
4.900e-03  2.100e+07  
1.300e-02  2.780e+07  

**Comments on Data**
Upper yield strength of the heavily doped crystals showed marked deviations from that of pure and low doped crystals over the range of strain rates studied. Behavior interpreted as solid solution hardening due to electrostatic interaction between dislocations and solute atoms.

**Reference**
THE INITIAL STAGE OF PLASTIC DEFORMATION OF SILICON HIGHLY DOPED WITH PHOSPHORUS.
Siethoff, H.
ACTA METALL.
17, 793-801, 1969.
Figure 190  Shear Strength,Resolved, Upper Yield of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Shear Strength, Resolved, Upper Yield

*****************************************************************************

Composition
1.e18 cm$^{-3}$ Oxygen Concentration
2.e16 cm$^{-3}$ Carbon Concentration

Vendor/Producer/Fabricator
KOFU Works of Hitachi Ltd.

Material Preparation
Crystal Growing Method:
Czochralski grown, dislocation free, n-type
Grown with diameter of 76 mm in the [111] direction.
Descriptors-Textual:
Annealed at 1323. K for various times.

Additional Preparation/Conditioning
Surface Treatment:
Surface layers polished and removed to depth more than 250 microns.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 7-9 Ω cm
Temperature 298 K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Test conducted in vacuum using Instrom machine mounted to high temperature apparatus. Resolved shear properties derived from measured data.
Parameters-Codified:
Pressure: 1.e-05 Torr
Shear Strain, Resolved: 1.1e-04 s[-1]
Temperature: 1173. K
Annealing Temperature: 1323. K

Measured/Evaluated Properties
X: Annealing Time s
Y : Shear Strength, Resolved, Upper Yield  
Z1 : Annealing Temperature  
Z2 : Temperature  
Z3 : Shear Strain Rate, Resolved  

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>3.540e+07</td>
<td>1.323e+03</td>
<td>1.173e+03</td>
<td>1.100e-04</td>
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<td>8.496e+03</td>
<td>3.290e+07</td>
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<td>1.173e+03</td>
<td>1.100e-04</td>
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<td>1.173e+03</td>
<td>1.100e-04</td>
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<tr>
<td>2.070e+04</td>
<td>1.030e+07</td>
<td>1.323e+03</td>
<td>1.173e+03</td>
<td>1.100e-04</td>
</tr>
<tr>
<td>4.169e+04</td>
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<td>1.173e+03</td>
<td>1.100e-04</td>
</tr>
<tr>
<td>8.474e+04</td>
<td>7.100e+06</td>
<td>1.323e+03</td>
<td>1.173e+03</td>
<td>1.100e-04</td>
</tr>
<tr>
<td>1.710e+05</td>
<td>9.300e+06</td>
<td>1.323e+03</td>
<td>1.173e+03</td>
<td>1.100e-04</td>
</tr>
</tbody>
</table>

Comments on Data
Yield strength decreased drastically with annealing time in the range of 0 to 10 hours; longer annealing time did not significantly reduce yield strength.

Reference
MECHANICAL BEHAVIOR OF CZOCHRALSKI-SILICON CRYSTALS AS AFFECTED BY PRECIPITATION AND DISSOLUTION OF OXYGEN ATOMS.
Yonenaga, I. Sumino, K.
JPN. J. APPL. PHYS.
Figure 191  Shear Strength, Resolved, Upper Yield of Silicon: P doped
Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
- Float-zone technique
- Crystal grown in a high purity argon gas atmosphere.

Descriptors-Textual:
- Dislocation density controlled by deformation at 1173 K and various strains (less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
- Orientation With Respect To Material: [123] Direction

Additional Properties
- Electrical Properties:
  - Electrical Resistivity: 460. Ω cm
  - Temperature: 298. K
- Other Properties-Numerical:
  - Dislocation Density: 2.0e04 cm⁻²
  - Temperature: 298. K

Measurement/Evaluation Method
- Name/Description:
  - Shear Response Under Tensile Loading
- Parameters-Textual:
  - Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of luders bands occurred.
- Parameters-Codified:
  - Pressure: 1.3e-02 Pa

Experimental Conditioning/Material Degradation
- Conditioning/Degradation/Environment: Vacuum Environment
- Descriptors-Numerical:
  - Pressure: 1.e-04 torr

Measured/Evaluated Properties
- X: Temperature: 101.3 K
- Y: Shear Strength, Resolved, Upper Yield: 1.3e01 Pa
$Z_1$ : Shear Strain Rate, Resolved $\text{s}^{-1}$

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.073e+03</td>
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<td>6.000e-04</td>
</tr>
<tr>
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<td>4.810e+07</td>
<td>6.000e-04</td>
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<tr>
<td>1.173e+03</td>
<td>1.950e+07</td>
<td>6.000e-04</td>
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<td>1.176e+03</td>
<td>2.120e+07</td>
<td>6.000e-04</td>
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<td>1.222e+03</td>
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</tr>
<tr>
<td>1.268e+03</td>
<td>3.800e+06</td>
<td>1.200e-04</td>
</tr>
</tbody>
</table>

Comments on Data
A graph of log yield strength vs. $1/T$ gave straight lines with an activation energy of 1.25 eV.

Reference
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I. Sumino, K.
PHYS. STATUS SOLIDI A
Figure 192  Shear Strength, Resolved, Upper Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Upper Yield

Vendor/Producer/Fabricator
Wacker

Material Preparation
Crystal Growing Method:
Float-zone grown, dislocation-free

Additional Preparation/Conditioning
Surface Treatment:
{111} and {541} side faces cut with a diamond saw and diamond polished (1/4 micron)

Specimen Identification
Dimensions (Geometry):
Length 14. mm
Thickness 4.25 mm
Width 4.25 mm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Specimen oriented to obtain a single slip deformation along {111} planes and <101> directions

Additional Properties
Electrical Properties:
Electrical Resistivity >5. Ω cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Compressive Loading

Measured/Evaluated Properties
X : Temperature K
Y : Shear Strength, Resolved, Upper Yield Pa
Z1 : Shear Strain Rate, Resolved s⁻¹

Data Points:
\begin{tabular}{|c|c|c|}
\hline
X & Y & Z1 \\
\hline
9.770e+02 & 3.820e+07 & 2.000e-05 \\
1.000e+03 & 3.420e+07 & 2.000e-05 \\
1.026e+03 & 1.810e+07 & 2.000e-05 \\
1.078e+03 & 1.020e+07 & 2.000e-05 \\
1.128e+03 & 6.400e+06 & 2.000e-05 \\
1.177e+03 & 4.200e+06 & 2.000e-05 \\
1.227e+03 & 3.600e+06 & 2.000e-05 \\
1.279e+03 & 3.400e+06 & 2.000e-05 \\
1.330e+03 & 3.000e+06 & 2.000e-05 \\
1.126e+03 & 2.490e+07 & 2.000e-04 \\
1.178e+03 & 1.100e+07 & 2.000e-04 \\
1.227e+03 & 9.000e+06 & 2.000e-04 \\
1.274e+03 & 4.800e+06 & 2.000e-04 \\
1.329e+03 & 4.000e+06 & 2.000e-04 \\
\hline
\end{tabular}

**Comments on Data**

At the lower strain rate, the temperature dependence consists of three stages. The low-temperature range in which the yield strength decreases rapidly with increasing temperature followed from about 1170 - 1320 K by a plateau where it remains constant or even slightly increases with temperature. At higher temperatures the flow stress extrapolated from stage I of easy glide decreases again. At higher strain rate the plateau no longer appears.

**Reference**

ON THE YIELD POINT OF FLOATING-ZONE SILICON SINGLE CRYSTALS. I. YIELD STRESSES AND ACTIVATION PARAMETERS.

Omri, M.  Tete, C.  Michel, J. P.  George, A.

PHILOS. MAG. A

Figure 193 Shear Strength, Resolved, Upper Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Upper Yield

********************************************

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
  Float-zone technique
  Crystal grown in a high purity argon gas atmosphere.
Descriptors-Textual:
  Dislocation density controlled by deformation at 1173 K and
  various strains (less than 10 pct shear strain). Specimens then
  subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity: 460. \( \Omega \, \text{cm} \)
  Temperature: 298. \( \text{K} \)

Measurement/Evaluation Method
Name/Description:
  Shear Response Under Tensile Loading
Parameters-Textual:
  Tensile tests using an Instron-Type machine. All specimens showed
  homogeneous deformation along gauge length. No deformation by
  means of the propagation of luders bands occurred.
Parameters-Codified:
  Pressure: 1.3e-02 \( \text{Pa} \)

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
  Pressure: 1.e-04 \( \text{torr} \)

Measured/Evaluated Properties
  X: Dislocation Density \( \text{m}^{-2} \)
  Y: Shear Strength, Resolved, Upper Yield \( \text{Pa} \)
  Z1: Temperature \( \text{K} \)
  Z2: Shear Strain Rate, Resolved \( \text{s}^{-1} \)
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
</tr>
</thead>
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<tr>
<td>1.700e+08</td>
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<td>1.200e-04</td>
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<td>5.300e+06</td>
<td>1.173e+03</td>
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<td>5.300e+06</td>
<td>1.173e+03</td>
<td>1.200e-04</td>
</tr>
</tbody>
</table>

Comments on Data
Dislocation density determined by etch-pit counting technique.
Yield strength decreases with increasing dislocation density.

Reference
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I., Sumino, K.
PHYS. STATUS SOLIDI A
Figure 194 Shear Strength, Resolved, Upper Yield of Silicon, n-type
MATERIAL: Silicon, n-type

PROPERTY: Shear Strength, Resolved, Upper Yield

Vendor/Producer/Fabricator
Semiconductor Division of Tokyo Shibaura Electric Company Ltd.

Material Preparation
Crystal Growing Method:
- Float-zone technique
- Crystal grown in a high purity argon gas atmosphere.
Descriptors-Textual:
- Dislocation density controlled by deformation at 1173 K and various strains (less than 10 pct shear strain). Specimens then subjected to thermal annealing for 24 hrs between 1273 and 1473 K.

Specimen Identification
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
- Electrical Resistivity: 460. Ω cm
- Temperature: 298. K
Other Properties-Numerical:
- Dislocation Density: 2.0e04 cm⁻²

Measurement/Evaluation Method
Name/Description:
- Shear Response Under Tensile Loading
Parameters-Textual:
- Tensile tests using an Instron-Type machine. All specimens showed homogeneous deformation along gauge length. No deformation by means of the propagation of lüders bands occurred.
Parameters-Codified:
- Pressure: 1.3e-02 Pa

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment
Descriptors-Numerical:
- Pressure: 1.e-04 torr

Measured/Evaluated Properties
X: Shear Strain Rate, Resolved
Y: Shear Strength, Resolved, Upper Yield
Z1: Temperature
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
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Comments on Data
Yield strength increases with increasing strain rate.

Reference
DISLOCATION DYNAMICS IN THE PLASTIC DEFORMATION OF SILICON CRYSTALS. I. EXPERIMENTS.
Yonenaga, I. Sumino, K.
PHYS. STATUS SOLIDI A
Figure 195 Shear Strength, Resolved, Upper Yield of Silicon, n-type
Material Preparation
Crystal Growing Method:
  Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
Surface Treatment:
The surfaces were lapped with diamond paste and chemically polished

Specimen Identification
Dimensions (Geometry):
  Length  15.  mm
  Width   3.4  mm
  Thickness  3.4  mm
Orientation With Respect To Material: [123] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity  200-1200  Ω cm
  Temperature  298.  K

Measurement/Evaluation Method
Name/Description:
  Shear Response Under Compressive Loading
  High-temperature apparatus mounted to Instron machine. Tests carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).
  Resolved shear properties derived from measured stress-strain curves.

Measured/Evaluated Properties
  X: Temperature  K
  Y: Shear Strength, Resolved, Upper Yield  Pa
  Z1: Shear Strain Rate, Resolved  s⁻¹

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658
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1.014e+03  8.110e+07  4.770e-04

Comments on Data
Observed results for pure silicon were analyzed by means of
dislocation theory. Dislocations move in viscous flow with an
activation energy of 2.3 eV.

Reference
THE YIELD POINT OF SILICON AND SILICON-GERMANIUM
SOLID SOLUTIONS.
Siethoff, H.
MATER. SCI. ENG.
Figure 196 Shear Strength, Resolved, Upper Yield of Silicon, p-type
Material Preparation
Crystal Growing Method:
Czochralski silicon grown in the [111] orientation.
Descriptors-Textual:
Specimens machined by ultrasonic mill and chemically polished

Specimen Identification
Dimensions (Geometry):
Length 3.4 cm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
Primary slip system along (1-11){10-1}.
Dog-bone shaped tensile specimens

Additional Properties
Electrical Properties:
Electrical Resistivity 10. - 21. \(\Omega\) cm
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Measurements made on an MTS materials tester. Shear properties
derived from measured tensile stress-strain.
Parameters-Codified:
Measurement Laboratory: Central Research Laboratories, Texas Instruments, Inc.,
Shear Strain Rate, Resolved: 5.5e-05 s[-1]
Temperature: 1073. K

Measured/Evaluated Properties
X: Oxygen Concentration ppm (atomic)
Y: Shear Strength,Resolved, Upper Yield Pa
Z1: Temperature K
Z2: Shear Strain Rate, Resolved s\(^{-1}\)

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**Comments on Data**

Data read from Figure 5.

Yield properties dominated by surface imperfections; dislocations can be nucleated which might account for the spread in data.

No significant effect of dissolved oxygen is seen on yield strength of as-grown crystals.

**Reference**

662
YIELD STRESS OF CZOCHRALSKI SILICON-THE EFFECT OF IMPURITIES AND OXYGEN PRECIPITATE MORPHOLOGY.
Lawrence, J. D. Tsai, H. L.
OXYGEN, CARBON, HYDROGEN AND NITROGEN IN CRYSTALLINE SILICON
( Edited by J. C. Mikkelsen, Jr., S. J. Pearton,
J. W. Corbett and S. J. Pennycook; Mater. Res. Soc:
Pittsburgh, Pennsylvania )
Figure 197  Shear Strength, Resolved, Upper Yield of Silicon, p-type
Material Preparation
Crystal Growing Method:
- Czochralski silicon grown in the [111] orientation.
Descriptors-Textual:
- Specimens machined by ultrasonic mill and chemically polished.
- Specimens annealed to cause oxygen precipitation.

Specimen Identification
Dimensions (Geometry):
- Length 3.4 cm
Orientation With Respect To Material: [123] Direction
Additional Identifiers:
- Primary slip system along (1-11){10-1}.
- Dog-bone shaped tensile specimens

Additional Properties
Electrical Properties:
- Electrical Resistivity 10. - 21. $\Omega$ cm
- Temperature 298. K
Other Properties-Textual:
- Specimens with an initial dissolved oxygen concentration of 29.5 +/- 0.5 ppm

Measurement/Evaluation Method
Name/Description:
- Shear Response Under Tensile Loading
- Measurements made on an MTS materials tester. Shear properties derived from measured tensile stress-strain.
Parameters-Codified:
- Measurement Laboratory: Central Research Laboratories, Texas Instruments, Inc.
- Shear Strain Rate, Resolved: 5.5e-05 s[-1]
- Temperature: 1073. K

Measured/Evaluated Properties
- X: Oxygen Concentration ppm (atomic)
- Y: Shear Strength, Resolved, Upper Yield Pa
- Z1: Temperature K
- Z2: Shear Strain Rate, Resolved s[-1]
- Z3: Carbon Concentration ppm (atomic)
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<td>1.500e+00</td>
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</tr>
<tr>
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<td>2.210e+07</td>
<td>1.073e+03</td>
<td>5.500e-05</td>
<td>1.500e+00</td>
<td></td>
</tr>
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<td>1.500e+00</td>
<td></td>
</tr>
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<td>1.500e+00</td>
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<tr>
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<td>5.500e-05</td>
<td>1.500e+00</td>
<td></td>
</tr>
</tbody>
</table>

Comments on Data

Data read from Figure 6.

**Value given as <0.5, annealed for 36 hrs. at 1323 K.

***Annealed for 16 hrs. at 1323 K.

Specimens contained an initial dissolved oxygen concentrations of 29.5 +/- 0.5 ppm.

Results show that carbon plays an indirect role in reducing the yield strength.

Reference

YIELD STRESS OF CZOCHRALSKE SILICON-THE EFFECT OF
IMPURITIES AND OXYGEN PRECIPITATE MORPHOLOGY.
Lawrence, J. D.  Tsai, H. L.
OXYGEN, CARBON, HYDROGEN AND NITROGEN IN
CRYSTALLINE SILICON
( Edited by J. C. Mikkelsen, Jr., S. J. Pearton,
J. W. Corbett and S. J. Pennycook; Mater. Res. Soc:
Pittsburgh, Pennsylvania )
Figure 198  Shear Strength, Resolved, Upper Yield of Silicon, p-type
Material Preparation
  Crystal Growing Method:
  Float-zone, p-type, dislocation free

Additional Preparation/Conditioning
  Surface Treatment:
  The surfaces were lapped with diamond paste and chemically polished

Specimen Identification
  Dimensions (Geometry):
    Length: 15. mm
    Width: 3.4 mm
    Thickness: 3.4 mm
  Orientation With Respect To Material: [123] Direction

Additional Properties
  Electrical Properties:
    Electrical Resistivity: 200-1200 Ω cm
    Temperature: 298. K

Measurement/Evaluation Method
  Name/Description:
  Shear Response Under Compressive Loading
  High-temperature apparatus mounted to Instron machine. Tests carried under an atmosphere of forming gas (92 pct N2, 8 pct H2).
  Resolved shear properties derived from measured stress-strain curves.

Measured/Evaluated Properties
  X: Shear Strain Rate, Resolved s⁻¹
  Y: Shear Strength, Resolved, Upper Yield Pa
  Z1: Temperature K

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.273e+03</td>
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<td>4.800e-04</td>
<td>2.940e+07</td>
<td>1.273e+03</td>
</tr>
<tr>
<td>1.200e-03</td>
<td>3.950e+07</td>
<td>1.273e+03</td>
</tr>
<tr>
<td>2.400e-03</td>
<td>4.260e+07</td>
<td>1.273e+03</td>
</tr>
<tr>
<td>4.900e-03</td>
<td>5.320e+07</td>
<td>1.273e+03</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
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</tr>
<tr>
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<tr>
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<td>1.173e+03</td>
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<tr>
<td>4.800e-04</td>
<td>4.500e+07</td>
<td>1.173e+03</td>
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<tr>
<td>1.200e-03</td>
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</tr>
<tr>
<td>2.400e-03</td>
<td>6.650e+07</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>4.900e-03</td>
<td>7.710e+07</td>
<td>1.173e+03</td>
</tr>
<tr>
<td>1.200e-02</td>
<td>9.640e+07</td>
<td>1.173e+03</td>
</tr>
</tbody>
</table>

**Comments on Data**
Observed results for pure silicon were analyzed by means of dislocation theory. Dislocations move in viscous flow with an activation energy of 2.3 eV.

**Reference**
THE YIELD POINT OF SILICON AND SILICON-GERMANIUM SOLID SOLUTIONS.
Siethoff, H.
MATER. SCI. ENG.
Figure 199 Shear Strength, Resolved, Upper Yield of Silicon, p-type
MATERIAL: Silicon

PROPERTY: Shear Strength, Resolved, Upper Yield

******************************************

**Composition**
16-20 ppm (atomic) Oxygen Concentration

**Material Preparation**
Crystal Growing Method:
- Dendritic web silicon ribbons grown along a \{211\} crystal orientation with \{111\} surfaces.
- Two thin single crystal sheets separated by odd number of twin planes.

**Additional Preparation/Conditioning**
Surface Treatment:
- Laser cut along length of ribbon, along [211] direction.
- After laser cut, mechanically polished with emery paper and diamond paste.
- Chemically polished using planar etch.

**Specimen Identification**
Dimensions (Geometry):
- Length 64.77 mm
- Width 21.60 mm
- Gauge-Section Thickness 25.40 mm
- Gauge-Section Width 12.80 mm

**Additional Identifiers**
- Multiple slip orientation along (111)[101] and (111)[110] systems

**Additional Properties**
Other Properties-Numerical:
- Dislocation Density: 1.e+06 cm\(^{-2}\)
- Temperature: 298. K

**Measurement/Evaluation Method**
Name/Description:
- Shear Response Under Tensile Loading
- Tensile axis of specimen is along the [211] direction, the ribbon growth direction.
- Constant extension rates in a high temperature testing chamber mounted on a servohydraulic MTS machine.
- Test performed in ultra high purity argon atmosphere.
- Heating by infrared elliptical furnace.

Parameters-Textual:
All specimens strained to 5 percent elongation.

Parameters-Codified:
Strain Rate : 1.e-05 to 5.e-04 [s-1]
Elongation : 5 percent

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.273e+03</td>
<td>1.040e+07</td>
<td>5.000e-04</td>
</tr>
<tr>
<td>1.473e+03</td>
<td>5.490e+06</td>
<td>5.000e-04</td>
</tr>
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<td>1.573e+03</td>
<td>6.470e+06</td>
<td>5.000e-04</td>
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<td>1.273e+03</td>
<td>5.790e+06</td>
<td>1.000e-04</td>
</tr>
<tr>
<td>1.373e+03</td>
<td>4.010e+06</td>
<td>1.000e-04</td>
</tr>
<tr>
<td>1.373e+03</td>
<td>3.730e+06</td>
<td>1.000e-04</td>
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<td>2.370e+06</td>
<td>1.000e-04</td>
</tr>
<tr>
<td>1.573e+03</td>
<td>3.490e+06</td>
<td>1.000e-04</td>
</tr>
<tr>
<td>1.173e+03</td>
<td>8.000e+06</td>
<td>1.000e-05</td>
</tr>
<tr>
<td>1.273e+03</td>
<td>4.450e+06</td>
<td>1.000e-05</td>
</tr>
<tr>
<td>1.373e+03</td>
<td>1.950e+06</td>
<td>1.000e-05</td>
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<tr>
<td>1.573e+03</td>
<td>7.750e+06</td>
<td>1.000e-05</td>
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</tbody>
</table>

**Comments on Data**
Data was digitized from Figures 2,3.
Strengthening effect above 1473 k, most significant for slowest strain rate.
Yield strength was also referred to as strength at 2% offset.

**Reference**
HIGH TEMPERATURE (900-1300 DEGREES C) MECHANICAL BEHAVIOR OF DENDRITIC WEB GROWN SILICON RIBBONS: STRAIN RATE AND TEMPERATURE DEPENDENCE OF THE YIELD STRESS.
Mathews, V. K. Gross, T. S.
SCR. METALL.
Figure 200  Shear Strength, Resolved, Upper Yield of Silicon
MATERIAL: Silicon

PROPERTY: Shear Strength, Resolved, Upper Yield

**Composition**

16-20 ppm (atomic) Oxygen Concentration

**Material Preparation**

Crystal Growing Method:
- Dendritic web silicon ribbons grown along a \{211\} crystal orientation with \{111\} surfaces.
- Two thin single crystal sheets separated by odd number of twin planes.

**Additional Preparation/Conditioning**

Descriptors-Numerical:
- Temperature 1573 K

Descriptors-Textual:
- Specimen allowed to age at 1573 K for various durations before experiment.

Surface Treatment:
- Laser cut along length of ribbon, along [211] direction.
- After laser cut, mechanically polished with emery paper and diamond paste.
- Chemically polished using planar etch.

**Specimen Identification**

Dimensions (Geometry):
- Length 64.77 mm
- Width 21.60 mm
- Gauge-Section Thickness 25.40 mm
- Gauge-Section Width 12.80 mm

Additional Identifiers:
- Multiple slip orientation along \(111\)\{101\} and \(111\)\{110\} systems

**Additional Properties**

Other Properties-Numerical:
- Dislocation Density 1.e+06 cm\(^{-2}\)
- Temperature 298. K

**Measurement/Evaluation Method**

Name/Description:
- Shear Response Under Tensile Loading
- Tensile axis of specimen is along the [211] direction, the ribbon growth direction.
Constant extension rates in a high temperature testing chamber mounted on a servohydraulic MTS machine. Test performed in ultra high purity argon atmosphere. Heating by infrared elliptical furnace.

Parameters-Textual:
All specimens strained to 5 percent elongation.

Parameters-Codified:
Strain Rate: 1.e-05 to 5.e-04 [s-1]
Elongation: 5 percent

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
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</thead>
<tbody>
<tr>
<td>0.000e+00</td>
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<td>1.573e+03</td>
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<td>6.760e+06</td>
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<td>1.000e-04</td>
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</table>

Data Points:

**Comments on Data**
Data was digitized from Figure 4. Higher degree of segregation with increase in aging time. Diffused oxygen atoms effectively lock dislocations resulting in higher strength with aging time. Yield strength was also referred to as strength at 2% offset.

**Reference**
HIGH TEMPERATURE (900-1300 DEGREES C) MECHANICAL BEHAVIOR OF DENDRITIC WEB GROWN SILICON RIBBONS: STRAIN RATE AND TEMPERATURE DEPENDENCE OF THE YIELD STRESS.
Mathews, V. K. Gross, T. S.
SCR. METALL.
Figure 201  Shear Strength, Resolved, Upper Yield of Silicon
MATERIAL: Silicon

PROPERTY: Shear Strength, Resolved, Upper Yield

**************************************************************************

Composition
16-20 ppm (atomic) Oxygen Concentration

Material Preparation
Crystal Growing Method:
Dendritic web silicon ribbons grown along a \{211\} crystal orientation with \{111\} surfaces.
Two thin single crystal sheets separated by odd number of twin planes.

Additional Preparation/Conditioning
Surface Treatment:
Laser cut along length of ribbon, along \{211\} direction.
After laser cut, mechanically polished with emery paper and diamond paste.
chemically polished using planar etch.

Specimen Identification
Dimensions (Geometry):

<table>
<thead>
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<th>Dimension</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
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<td>Length</td>
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</tr>
<tr>
<td>Width</td>
<td>21.60</td>
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<tr>
<td>Gauge-Section Thickness</td>
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<td>mm</td>
</tr>
<tr>
<td>Gauge-Section Width</td>
<td>12.80</td>
<td>mm</td>
</tr>
</tbody>
</table>

Additional Identifiers:
Multiple slip orientation along \{111\}\{101\} and \{111\}\{110\} systems

Additional Properties
Other Properties-Numerical:

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<tr>
<th>Property</th>
<th>Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Dislocation Density</td>
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<td>cm$^{-2}$</td>
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<tr>
<td>Temperature</td>
<td>298.</td>
<td>K</td>
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</tbody>
</table>

Measurement/Evaluation Method
Name/Description:
Shear Response Under Tensile Loading
Tensile axis of specimen is along the \{211\} direction, the ribbon growth direction.
Constant extension rates in a high temperature testing chamber mounted on a servohydraulic MTS machine.
Test performed in ultra high purity argon atmosphere.
Heating by infrared elliptical furnace.

Parameters-Textual:
All specimens strained to 5 percent elongation.

Parameters-Codified:

Strain Rate : 1.e-05 to 5.e-04 [s⁻¹]
Elongation : 5 percent

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
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<td>5.100e-04</td>
<td>6.380e+06</td>
<td>1.573e+03</td>
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</table>

**Comments on Data**

Data was digitized from Figure 2.
Positive strain rate dependence for temperatures up to 1473 K.
At 1573 K there is a sharp change in the slope, and a negative strain rate dependence is observed.
Upper yield strength was also referred to as strength at 2 percent offset.

**Reference**

HIGH TEMPERATURE (900-1300 DEGREES C) MECHANICAL BEHAVIOR OF DENDRITIC WEB GROWN SILICON RIBBONS: STRAIN RATE AND TEMPERATURE DEPENDENCE OF THE YIELD STRESS.
Mathews, V. K. Gross, T. S.
SCR. METALL.
Figure 202  Shear Strength, Resolved, Upper Yield of Silicon
Material Preparation
Crystal Growing Method:
Floating-Zone (FZ)

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Pre-cracked specimens were annealed in oxygen for at least 2 hours at 1100 C, 4 hours at 1000 C, or 10 hours at 900 C in order to heal the precursor cracks.

Material Microstructure
Dislocation-free 100 mm diameter (001) wafers
Interstitial oxygen (infra-red absorption): 1.0e+16 cm[-3] in FZ crystals.
Substitutional carbon content was below instrumental detection limit

Specimen Identification
Dimensions (Geometry):
- Length: 32 mm
- Width: 4 mm
- Thickness: 0.5 mm
Orientation With Respect To Material: [100] Direction

Additional Properties
Electrical Properties:
- Electrical Resistivity: 17-23 Ω cm
- Temperature: 295 K

Measurement/Evaluation Method
Name/Description:
Four-Point Flexure on Pre-Cracked Specimens
Four-point bend test on pre-cracked and subsequently oxygen-annealed specimens.
Parameters-Codified:
Cross-Head Speed: 0.02 mm min[-1]

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa
Data Points:

\[ X \quad Y \quad \text{Remarks:} \]
\[ 2.950e+02 \quad 4.000e+08 \quad \text{Data Scatter = +/- 50 MPa (approx.)} \]

Comments on Data
Precursor cracks healed by annealing at from 900 C to 1100 C for an appropriate time.
The healing mechanism is the growth of a bonding layer of SiO(2), which proceeds as a reaction-rate-limited growth process.

Reference
CRACK HEALING AND FRACTURE STRENGTH OF SILICON CRYSTALS.
Yasutake, K. Iwata, M. Yoshii, K.
Umeno, M. Kawabe, H.
J. MATER. SCI.
21 (6), 2185-92, 1986.
Figure 203 Flexural Strength of Silicon: B doped
Composition

8e+17 cm\(^{-3}\) Oxygen Concentration
8e+15 cm\(^{-3}\) Boron Dopant Concentration

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO\(_3\):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, p-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Argon Environment

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>6.200e+09</td>
<td>Standard Deviation = 450 MPa</td>
</tr>
</tbody>
</table>

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B., Turovskii, B. M.
Mezhennyi, M. V., Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 204 Flexural Strength of Silicon: B doped
**Composition**

3e+17 cm^{-3} Oxygen Concentration
3e+16 cm^{-3} Boron Dopant Concentration

**Material Preparation**

Crystal Growing Method:
Czochralski

**Additional Preparation/Conditioning**

Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

**Material Microstructure**

Dislocation-free material, p-type

**Specimen Identification**

Orientation With Respect To Material: (111) Plane

**Measurement/Evaluation Method**

Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

**Experimental Conditioning/Material Degradation**

Conditioning/Degradation/Environment: Vacuum Environment

**Measured/Evaluated Properties**

X : Temperature  \( K \)
Y : Flexural Strength  \( \text{Pa} \)
Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks:} \\
2.950\times10^2 & 6.120\times10^9 & \text{Standard Deviation} = 450 \text{ MPa}
\end{array}
\]

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 205 Flexural Strength of Silicon: B doped
MATERIAL: Silicon: B doped
PROPERTY: Flexural Strength

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3):conc. HF=2:1) to remove an additional 180 micron (approx.).
This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, p-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter.
Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.
Dopant concentrations were determined from standard electrical property measurements.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Measured/Evaluated Properties
X : Temperature
Y : Flexural Strength
Z1: Boron Dopant Concentration

K
Pa
m^{-3}
Data Points:

<table>
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<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks</th>
</tr>
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<tr>
<td>2.950e+02</td>
<td>5.400e+07</td>
<td>5.000e+20</td>
<td>S.D. = 5.1 MPa, As-Cut Condition</td>
</tr>
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<td>2.950e+02</td>
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<td>2.500e+25</td>
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<td>S.D. = 7.1 MPa, As-Cut + Grounded</td>
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<td>2.500e+25</td>
<td>S.D. = 6.0 MPa</td>
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<td>S.D. = 320 MPa</td>
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<td>6.920e+09</td>
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<td>S.D. = 550 MPa</td>
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<td>2.950e+02</td>
<td>8.340e+09</td>
<td>1.500e+25</td>
<td>S.D. = 630 MPa</td>
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<tr>
<td>2.950e+02</td>
<td>9.660e+09</td>
<td>2.500e+25</td>
<td>S.D. = 730 MPa</td>
</tr>
</tbody>
</table>

**Comments on Data**

Number of specimens was at least 15 per condition or dopant concentration.
High concentrations of boron dopant noticeably enhance the flexural strength.

**Reference**

FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 206 Flexural Strength of Silicon: B doped
Material Preparation
Crystal Growing Method:
Float-Zoned

Additional Preparation/Conditioning
Surface Treatment:
As-received wafers had one mirror finish surface (tension surface) and one deep etched surface (compression surface). The deep etched surface was heavily etched with CP4 (HF:HNO(3):glacial acetic acid = 3:5:3).

Specimen Identification
Number/Name: Float-Zoned Si:B
Orientation With Respect To Material: (100) Plane

Additional Properties
Electrical Properties:
   Electrical Resistivity >600 \( \Omega \text{ cm} \)
   Temperature 295 \( \text{K} \)

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers.
Circular aluminum platform had 5 mm diameter hole with a beveled edge to provide concentric support.
Load was applied by a 5 mm ball attached to an Instron machine.
Crosshead speed was 100 micron/min.
Fracture load was converted to flexure strength (tensile surface stress at fracture) using elastic bending theory.

Measured/Evaluated Properties
X : Thickness \( \text{m} \)
Y : Flexural Strength \( \text{Pa} \)
Z1 : Temperature \( \text{K} \)

Data Points:
\[
\begin{array}{cccc}
X & Y & Z1 & \text{Remarks} \\
3.810e-04 & 3.100e+09 & 2.950e+02 & \text{S.D.=0.6 GPa, Un-etched} \\
4.570e-04 & 3.300e+09 & 2.950e+02 & \text{S.D.=1.0 GPa, Un-etched} \\
5.080e-04 & 3.000e+09 & 2.950e+02 & \text{S.D.=0.4 GPa, Un-etched} \\
\end{array}
\]
3.930e-04  3.400e+09  2.950e+02  S.D.=1.0 GPA, Etched from 457 mic.
4.050e-04  6.700e+09  2.950e+02  S.D.=1.4 GPa, Etched from 508 mic.

**Comments on Data**
Number of specimens was eight per thickness.
Surface morphology on compression side is considered to be the
dominating factor in determining the fracture stress for
float-zoned material.

**Reference**
FRACTURE OF SILICON WAFERS.
McLaughlin, J. C. Willoughby, A. F. W.
J. CRYST. GROWTH
Figure 207 Flexural Strength of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Flexural Strength

********************************************************************************

Vendor/Producer/Fabricator
Mitsubishi Electric Corp.

Material Preparation
Crystal Growing Method:
Czochralski-grown crystals

Specimen Identification
Dimensions (Geometry):
Length 32. mm
Width 5.0 mm
Thickness 0.53 mm
Orientation With Respect To Material: [110] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 15-25 $\Omega \text{ cm}$
Temperature 298. K
Other Properties-Numerical:
Oxygen Concentration 11.5e17 $\text{cm}^{-3}$
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Four-Point Bend Test
Parameters-Textual:
Four-point loading device made of quartz and the distances between inner and outer knife-edges are 8 and 24 mm, respectively.
The device was attached to an Instron machine.
Parameters-Codified:
Strain Rate: 1.5e-06 $\text{s}^{-1}$

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa

Data Points:

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<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
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<td>2.950e+02</td>
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697
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<th>Value 2</th>
<th>Description</th>
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<tr>
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<tr>
<td>4.780e+02</td>
<td>2.170e+08</td>
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<td>5.810e+02</td>
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<td>6.770e+02</td>
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<tr>
<td>8.360e+02</td>
<td>4.207e+08</td>
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<tr>
<td>8.560e+02</td>
<td>3.424e+08</td>
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</tr>
<tr>
<td>8.760e+02</td>
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<tr>
<td>9.230e+02</td>
<td>1.793e+08</td>
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**Comments on Data**

Data was digitized from figure 2.
Fracture strength of the as-received CZ-wafers increases with T and becomes maximum at T approximately 793 K. In the T range 823-873 K, they fracture at almost the level of the yield strength, and at above 923 K, they become entirely ductile.

**Reference**

MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON WAFERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.
Yasutake, K. Murakami, J. Umeno, M.
Kawabe, H.
JPN. J. APPL. PHYS., PART 2
Figure 208 Flexural Strength of Silicon: B doped
**MATERIAL:** Silicon: B doped  
**PROPERTY:** Flexural Strength  
**-----------------------------------------------**  
**-----------------------------------------------**  
**Vendor/Producer/Fabricator**  
Mitsubishi Electric Corp.  
**Material Preparation**  
Crystal Growing Method:  
Floating-zone-grown crystals.  
**Specimen Identification**  
Dimensions (Geometry):  
Length: 32. mm  
Width: 5.0 mm  
Thickness: 0.53 mm  
Orientation With Respect To Material: [110] Direction  
**Additional Properties**  
Electrical Properties:  
Electrical Resistivity: 15-25 $\Omega$ cm  
Temperature: 298. K  
**Measurement/Evaluation Method**  
Name/Description:  
Four-Point Bend Test  
Parameters-Textual:  
Four-point loading device made of quartz and the distances between inner and outer knife-edges are 8 and 24 mm, respectively.  
The device was attached to an Instron machine.  
Parameters-Codified:  
Strain Rate: 1.5e-06 s[-1]  
**Measured/Evaluated Properties**  
$X$ : Temperature  
$Y$ : Flexural Strength  
**Data Points:**  

<table>
<thead>
<tr>
<th>$X$</th>
<th>$Y$</th>
<th>Remarks:</th>
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<tbody>
<tr>
<td>2.950e+02</td>
<td>1.806e+08</td>
<td>fracture</td>
</tr>
<tr>
<td>3.830e+02</td>
<td>1.922e+08</td>
<td></td>
</tr>
<tr>
<td>4.780e+02</td>
<td>1.928e+08</td>
<td></td>
</tr>
<tr>
<td>5.810e+02</td>
<td>2.380e+08</td>
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</table>
6.810e+02  2.768e+08  
7.800e+02  5.317e+08  
8.000e+02  5.321e+08  
8.280e+02  5.021e+08  yield,fracture  
8.560e+02  3.853e+08  
8.760e+02  2.706e+08  

Comments on Data
Data was digitized from figure 2
Fracture strength of as-received float-zone-grown wafers
increases with T and becomes maximum at T approximately
793 K. At T = 823-873 K, wafers fracture at almost the
level of the yield strength, and at above 923 K, they
become entirely ductile.

Reference
MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON
WAVERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.
Yasutake, K. Murakami, J. Umeno, M.
Kawabe, H.
JPN. J. APPL. PHYS., PART 2
Figure 209 Flexural Strength of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Flexural Strength

******************************************************************************

Vendor/Producer/Fabricator
Mitsubishi Electric Corp.

Material Preparation
Crystal Growing Method:
Czochralski-grown crystals
Descriptors-Textual:
Chemically polished and then annealed at 1073 K for 100 hrs.

Specimen Identification
Dimensions (Geometry):
Length 32. mm
Width 5.0 mm
Thickness 0.53 mm
Orientation With Respect To Material: [110] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 15-25 Ω cm
Temperature 298. K
Other Properties-Textual:
Etch pit density: approx. 8.0e09 cm[-3]
SiO(2) precipitate size: approx. 4200 Angstroms.

Measurement/Evaluation Method
Name/Description:
Four-Point Bend Test
Parameters-Textual:
Four-point loading device made of quartz and the distances
between inner and outer knife-edges are 8 and 24 mm,
respectively.
The device was attached to an Instron machine.
Parameters-Codified:
Strain Rate: 1.5e-06 s[-1]

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa

Data Points:
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<th>X</th>
<th>Y</th>
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<tr>
<td>4.780e+02</td>
<td>1.615e+08</td>
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<td>4.790e+02</td>
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<td>7.330e+02</td>
<td>2.392e+08</td>
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<tr>
<td>7.800e+02</td>
<td>4.199e+08</td>
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</tbody>
</table>

**Comments on Data**

Data was digitized from figure 2
Fracture strength at room temperature does not change with heat treatments if surface-denuded zones (DZ) present.
Platelike SiO(2) precipitates of about 10.e10cm[-3] are observed by TEM and etch-pit method, but no punched-out dislocation loops exist. Annealed CZ wafers become ductile at T above 793 K.

**Reference**

MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON WAFERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.
Yasutake, K. Murakami, J. Umeno, M.
Kawabe, H.
JPN. J. APPL. PHYS., PART 2
Figure 210 Flexural Strength of Silicon: B doped
Composition
3e+16 cm\(^{-3}\) Gallium Dopant Concentration

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO\(_3\):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, p-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure
Axisymmetric bending method employing pneumatic loading. A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Argon Environment

Measured/Evaluated Properties
X : Temperature \( \text{K} \)
Y : Flexural Strength \( \text{Pa} \)
Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks:}\ \text{Standard Deviation} = 430 \text{ MPa} \\
2.950e+02 & 6.150e+09 & \\
\end{array}
\]

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
(FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985)
Figure 211  Flexural Strength of Silicon: Ga doped
MATERIAL: Silicon: Ga doped

PROPERTY: Flexural Strength

Composition
3e+16 cm\(^{-3}\) Gallium Dopant Concentration

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28(boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO\(_3\):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, p-type

Specimen Identification
Orientation With Respect To Material: (100) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure
Axisymmetric bending method employing pneumatic loading.
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Argon Environment

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa
Data Points:

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<th>X</th>
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<th>Remarks: Standard Deviation = 410 MPa</th>
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<td>2.950e+02</td>
<td>6.310e+09</td>
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</tr>
</tbody>
</table>

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B.     Turovskii, B. M.
Mezhennyi, M. V.     Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 212  Flexural Strength of Silicon: Ga doped
**Material Preparation**
Crystal Growing Method:
Czochralski

**Additional Preparation/Conditioning**
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28(boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

**Material Microstructure**
Dislocation-free material, p-type

**Specimen Identification**
Orientation With Respect To Material: (111) Plane

**Measurement/Evaluation Method**
Name/Description:
Pneumatically Loaded Wafer Flexure
Axisymmetric bending method employing pneumatic loading. A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory. Dopant concentrations were determined from standard electrical property measurements.

**Experimental Conditioning/Material Degradation**
Conditioning/Degradation/Environment: Vacuum Environment

**Measured/Evaluated Properties**
X: Gallium Dopant Concentration \( m^{-3} \)
Y: Flexural Strength \( Pa \)
Z1: Temperature \( K \)
Data Points:

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<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
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</thead>
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<tr>
<td>1.000e+21</td>
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<td>2.950e+02</td>
<td>S.D. = 3.9 MPa, As-Cut Condition</td>
</tr>
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<td>3.000e+24</td>
<td>5.400e+07</td>
<td>2.950e+02</td>
<td>S.D. = 4.1 MPa</td>
</tr>
<tr>
<td>1.000e+21</td>
<td>6.400e+07</td>
<td>2.950e+02</td>
<td>S.D. = 4.2 MPa, As-Cut + Ground</td>
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<td>S.D. = 6.3 MPa</td>
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<td>1.000e+21</td>
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<td>S.D. = 440 MPa, Chem. Etched</td>
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<td>S.D. = 480 MPa</td>
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</tbody>
</table>

Comments on Data
The number of specimens was at least 15 per condition or dopant concentration.
High concentration of gallium dopant noticeably enhances the flexural strength.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B.  Turovskii, B. M.
Mezhennyi, M. V.  Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
(FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 ( 3 ), 299-302, 1985)
Figure 213 Flexural Strength of Silicon: Ga doped
MATERIAL: Silicon: P doped

PROPERTY: Flexural Strength

*************************************************

Composition
5e+14 cm⁻³ Phosphorus Dopant Concentration
2e+16 cm⁻³ Oxygen Concentration

Material Preparation
Crystal Growing Method:
Crucibleless zonal melting

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO₃:conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, n-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Measured/Evaluated Properties
X : Temperature K
Y : Flexural Strength Pa
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>6.000e+09</td>
<td>Standard Deviation = 530 MPa</td>
</tr>
</tbody>
</table>

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 214  Flexural Strength of Silicon: P doped
**Composition**

\[
\begin{align*}
4e+17 & \text{ cm}^{-3} \\
9e+15 & \text{ cm}^{-3}
\end{align*}
\]

- Oxygen Concentration
- Phosphorus Dopant Concentration

**Material Preparation**

Crystal Growing Method :
Czochralski

**Additional Preparation/Conditioning**

Surface Treatment :
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28(boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3);conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

**Material Microstructure**

Dislocation density = 1.0e+4 cm[-2]; n-type material

**Specimen Identification**

Orientation With Respect To Material : (111) Plane

**Measurement/Evaluation Method**

Name/Description :
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory.

**Experimental Conditioning/Material Degradation**

Conditioning/Degradation/Environment : Vacuum Environment

**Measured/Evaluated Properties**

- X : Temperature \( \text{K} \)
- Y : Flexural Strength \( \text{Pa} \)
Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks:} \\
2.950e+02 & 6.050e+09 & \text{Standard Deviation = 480 MPa}
\end{array}
\]

Comments on Data
Number of specimens was at least 15.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEOR. MATER.
(FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985)
Figure 215  Flexural Strength of Silicon: P doped
Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28(boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3):conc. HF=2:1) to remove an additional 180 micron (approx.).
This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, n-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory. Dopant concentrations were determined from standard electrical property measurements.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength Pa
Z1: Phosphorus Dopant Concentration m⁻³
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>4.200e+07</td>
<td>9.000e+21</td>
<td>S.D. = 3.7 MPa, As-Cut Condition</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>4.800e+07</td>
<td>2.000e+25</td>
<td>S.D. = 5.1 MPa</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>5.500e+07</td>
<td>9.000e+21</td>
<td>S.D. = 4.9 MPa, As-Cut + Ground</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>7.600e+07</td>
<td>2.000e+25</td>
<td>S.D. = 6.9 MPa</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>6.110e+09</td>
<td>9.000e+21</td>
<td>S.D. = 420 MPa, Chemically Etched</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>5.840e+09</td>
<td>1.500e+22</td>
<td>S.D. = 360 MPa</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>6.370e+09</td>
<td>1.500e+24</td>
<td>S.D. = 540 MPa</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>7.600e+09</td>
<td>8.000e+24</td>
<td>S.D. = 570 MPa</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>9.300e+09</td>
<td>2.000e+25</td>
<td>S.D. = 740 MPa</td>
</tr>
</tbody>
</table>

Comments on Data
Number of specimens measured was at least 15 per condition or dopant concentration.
High concentrations of phosphorus dopant noticeably enhance the flexural strength.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
(FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985)
Figure 216  Flexural Strength of Silicon: P doped
MATERIAL: Silicon: Sb doped

PROPERTY: Flexural Strength

******************************************************************************

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both surfaces were ground with M-28 (boron carbide) powder to remove a layer from 60 to 100 microns thick, and then were chemically polished (conc. HNO(3):conc. HF=2:1) to remove an additional 180 micron (approx.). This surface treatment ensured virtually complete removal of surface damage.

Material Microstructure
Dislocation-free material, n-type

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading on a silicon wafer freely supported by a ring support. A vacuum lubricant was applied to the wafer-ring interface. Gas pressures up to 20 MPa permitted application of a total load amounting to 12 kN to the surface of rings up to 90mm in diameter. Fracture strength was computed from pressure, diameter, and thickness by applying simple theory. Dopant concentrations were determined from standard electrical property measurements.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Vacuum Environment

Measured/Evaluated Properties
X: Antimony Dopant Concentration m^-3
Y: Flexural Strength Pa
Z1: Temperature K

724
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.000e+21</td>
<td>4.300e+07</td>
<td>2.950e+02</td>
<td>S.D. = 3.9 MPa, As-Cut Condition</td>
</tr>
<tr>
<td>3.000e+24</td>
<td>4.400e+07</td>
<td>2.950e+02</td>
<td>S.D. = 3.6 MPa</td>
</tr>
<tr>
<td>3.000e+21</td>
<td>7.000e+07</td>
<td>2.950e+02</td>
<td>S.D. = 5.8 MPa, As-Cut + Ground</td>
</tr>
<tr>
<td>3.000e+24</td>
<td>6.600e+07</td>
<td>2.950e+02</td>
<td>S.D. = 4.9 MPa</td>
</tr>
<tr>
<td>3.000e+21</td>
<td>5.850e+09</td>
<td>2.950e+02</td>
<td>S.D. = 340 MPa, Chemically Etched</td>
</tr>
<tr>
<td>6.000e+22</td>
<td>5.790e+09</td>
<td>2.950e+02</td>
<td>S.D. = 480 MPa</td>
</tr>
<tr>
<td>3.000e+23</td>
<td>5.230e+09</td>
<td>2.950e+02</td>
<td>S.D. = 300 MPa</td>
</tr>
<tr>
<td>2.000e+24</td>
<td>5.050e+09</td>
<td>2.950e+02</td>
<td>S.D. = 290 MPa</td>
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<tr>
<td>3.000e+24</td>
<td>4.460e+09</td>
<td>2.950e+02</td>
<td>S.D. = 230 MPa</td>
</tr>
</tbody>
</table>

Comments on Data
The number of specimens was at least 15 per surface condition and dopant concentration.
High concentrations of antimony dopant noticeably reduced the flexural strength.

Reference
FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 217 Flexural Strength of Silicon: Sb doped
**Material Preparation**
Crystal Growing Method:
Czochralski

**Additional Preparation/Conditioning**
Surface Treatment:
Subsequent to cutting the wafers with a diamond saw, both
surfaces were ground with M-28(boron carbide) powder to remove
a layer from 60 to 100 microns thick, and then were chemically
polished (conc. HNO(3):conc. HF=2:1) to remove an additional
180 micron (approx.).
This surface treatment ensured virtually complete removal of
surface damage.

**Material Microstructure**
Dislocation-free material

**Specimen Identification**
Orientation With Respect To Material : (111) Plane

**Measurement/Evaluation Method**
Name/Description:
Pneumatically Loaded Wafer Flexure Test
A no-contact loading method utilized gas pressure loading
on a silicon wafer freely supported by a ring support. A vacuum
lubricant was applied to the wafer-ring interface. Gas pressures
up to 20 MPa permitted application of a total load amounting to
12 kN to the surface of rings up to 90mm in diameter.
Fracture strength was computed from pressure, diameter, and
thickness by applying simple theory.
Dopant concentrations were determined from standard electrical
property measurements.

**Experimental Conditioning/Material Degradation**
Conditioning/Degradation/Environment : Vacuum Environment

**Measured/Evaluated Properties**
X : Tin Dopant Concentration [m⁻³]
Y : Flexural Strength [Pa]
Z₁ : Temperature [K]
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.000e+23</td>
<td>6.400e+07</td>
<td>2.950e+02</td>
<td>S.D. = 4.1 MPa, As-Cut Condition</td>
</tr>
<tr>
<td>7.000e+23</td>
<td>6.700e+07</td>
<td>2.950e+02</td>
<td>S.D. = 5.3 MPa</td>
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<tr>
<td>2.000e+23</td>
<td>7.400e+07</td>
<td>2.950e+02</td>
<td>S.D. = 560 MPa, As-Cut + Ground</td>
</tr>
<tr>
<td>7.000e+23</td>
<td>7.500e+07</td>
<td>2.950e+02</td>
<td>S.D. = 4.2 MPa</td>
</tr>
<tr>
<td>2.000e+23</td>
<td>4.500e+09</td>
<td>2.950e+02</td>
<td>S.D. = 510 MPa, Chemically Etched</td>
</tr>
<tr>
<td>7.000e+23</td>
<td>4.350e+09</td>
<td>2.950e+02</td>
<td>S.D. = 450 MPa</td>
</tr>
</tbody>
</table>

Comments on Data

The number of specimens was at least 15 per surface condition and dopant concentration. High concentrations of tin dopant noticeably reduced the flexural strength.

Reference

FACTORS AFFECTING THE BULK STRENGTH OF SILICON SINGLE CRYSTALS.
Osvenskii, V. B. Turovskii, B. M.
Mezhennyi, M. V. Sokolova, E. L.
Stolyarov, O. G.
IZV. AKAD. NAUK SSSR, NEORG. MATER.
( FOR ENGLISH TRANSLATION SEE INORG. MATER.,
21 (3), 299-302, 1985 )
Figure 218 Flexural Strength of Silicon: Sn doped
Material Preparation
Crystal Growing Method:
Float-Zoned

Additional Preparation/Conditioning
Surface Treatment:
As-received wafers had one mirror finish surface (tension surface) and one deep etched surface (compression surface).
The deep etched surface was heavily etched with CP4 (HF:HNO(3):glacial acetic acid = 3:5:3).

Specimen Identification
Number/Name: Float-zone p-type silicon, hydrogen-anneal effect.
Orientation With Respect To Material: (100) Plane

Additional Properties
Electrical Properties:
Electrical Resistivity: >30 Ω cm
Temperature: 295 K

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers.
Circular aluminum platform had 5 mm diameter hole with a beveled edge to provide concentric support.
Load was applied by a 5 mm ball attached to an Instron machine.
Crosshead speed was 100 micron/min.
Fracture load was converted to flexure strength (tensile surface stress at fracture) using elastic bending theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Hydrogen Environment
Descriptors-Numerical:
Annealing Temperature: 1250 °C

Measured/Evaluated Properties
X: Annealing Time
Y: Flexural Strength

Data Points:
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>2.000e+09</td>
<td>S.D. = 0.16 GPa, No. specimens = 8</td>
</tr>
<tr>
<td>5.400e+03</td>
<td>4.200e+09</td>
<td>S.D. = 0.85 GPa, No. specimens = 8</td>
</tr>
</tbody>
</table>

**Comments on Data**
Fracture strength enhancement is thought to be due to annealing of imperfections on the wafer backface (compression side).

**Reference**
FRACTURE OF SILICON WAFERS.
McLaughlin, J. C. Willoughby, A. F. W.
J. CRYS'T. GROWTH
Figure 219 Flexural Strength of Silicon, p-type
**Material Preparation**
Crystal Growing Method:
- Float-Zoned

**Additional Preparation/Conditioning**
Surface Treatment:
- As-received wafers had one mirror finish surface (tension surface) and one deep etched surface (compression surface).
- The deep etched surface was heavily etched with CP4 (HF:HNO(3):glacial acetic acid = 3:5:3).

**Specimen Identification**
Number/Name: Float-zone p-type silicon, oxidation effect
- Sample Series A, B, C, D, E, F, G, and H.
- Orientation With Respect To Material: (100) Plane

**Additional Properties**
Electrical Properties:
- Electrical Resistivity = 30 Ω cm
- Temperature = 295 K

**Measurement/Evaluation Method**
Name/Description:
- Ball-and-Ring Flexure Test for Wafers.
- Circular aluminum platform had 5 mm diameter hole with a beveled edge to provide concentric support.
- Load was applied by a 5 mm ball attached to an Instron machine.
- Crosshead speed was 100 micron/min.
- Fracture load was converted to flexure strength (tensile surface stress at fracture) using elastic bending theory.

**Experimental Conditioning/Material Degradation**
Conditioning/Degradation/Environment: Oxidation Treatment
Descriptors-Numerical:
- Annealing Temperature = 1250 °C
Descriptors-Textual:
- Dry oxide layers 0.70 micron in thickness were grown on the wafers.

**Measured/Evaluated Properties**
X: Oxidation Time = s
Y : Flexural Strength  

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>2.000e+09</td>
<td>S.D.=0.15 GPa, Control Series</td>
</tr>
<tr>
<td>5.760e+04</td>
<td>3.300e+09</td>
<td>S.D.=0.39 GPa, CP + O</td>
</tr>
<tr>
<td>5.760e+04</td>
<td>2.400e+09</td>
<td>S.D.=0.40 GPa, CP + O + E</td>
</tr>
<tr>
<td>5.760e+04</td>
<td>3.000e+09</td>
<td>S.D.=0.21 GPa, O</td>
</tr>
<tr>
<td>5.760e+04</td>
<td>2.000e+09</td>
<td>S.D.=0.07 GPa, O + E</td>
</tr>
<tr>
<td>1.152e+05</td>
<td>3.200e+09</td>
<td>S.D.=0.51 GPa, O + E + O</td>
</tr>
<tr>
<td>1.152e+05</td>
<td>2.000e+09</td>
<td>S.D.=0.48 GPa, O(2) + E(2)</td>
</tr>
<tr>
<td>6.584e+04</td>
<td>2.100e+09</td>
<td>S.D.=0.56 GPa, O + E + PO</td>
</tr>
</tbody>
</table>

Comments on Data

Surface-treatment (oxidation) test series are identified by:
- CP = Chemical Polish
- O = Oxidation
- PO = Partial Oxidation
- E = Etched to remove oxide

Number of specimens was eight per test series.
An oxide layer 0.70 micron thickness on the compression side is observed to increase the fracture strength.

Reference

FRACTURE OF SILICON WAFERS.
McLaughlin, J. C. Willoughby, A. F. W.
J. CRYST. GROWTH
Figure 220  Flexural Strength of Silicon, p-type
MATERIAL: Silicon, p-type

PROPERTY: Flexural Strength

****************************************

Material Preparation
Crystal Growing Method:
  Float-Zoned

Additional Preparation/Conditioning
Surface Treatment:
  As-received wafers had one mirror finish surface (tension surface) and one deep etched surface (compression surface).
  The deep etched surface was heavily etched with CP4 (HF:HNO(3):glacial acetic acid = 3:5:3).

Specimen Identification
Number/Name: Float-Zone p-type silicon, implantation and RTA effect
Orientation With Respect To Material: (100) Plane

Additional Properties
Electrical Properties:
  Electrical Resistivity >30 Ω cm
  Temperature 295 K

Measurement/Evaluation Method
Name/Description:
  Ball-and-Ring Flexure Test for Wafers.
  Circular aluminum platform had 5 mm diameter hole with a beveled edge to provide concentric support.
  Load was applied by a 5 mm ball attached to an Instron machine.
  Crosshead speed was 100 micron/min.
  Fracture load was converted to flexure strength (tensile surface stress at fracture) using elastic bending theory.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Ion Implantation
Descriptors-Numerical:
  Annealing Temperature 1250 °C
Descriptors-Textual:
  Ion-implantation parameters: Ge(+) with 1.0e+15 cm[-2] dosage.
  Ion-implantation parameters: B(+) with 1.0e+15 cm[-2]
  Ion-implantation parameters: B(+) with 1.0e+16 cm[-2]
  Ion-implantation parameters: Sb(+) with 3.76e+14 cm[-2]
  Ion-implantation parameters: Sb(+) with 3.76e+15 cm[-2]
  Implantation was followed by rapid thermal anneal(RTA)
**Measured/Evaluated Properties**

X : Annealing Time
Y : Flexural Strength

**Data Points :**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.770e+04</td>
<td>2.300e+09</td>
<td>S.D.=0.1 GPa,B(+) 1.0e+15 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>2.200e+09</td>
<td>S.D.=0.4 GPa,B(+) 1.0e+16 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>2.200e+09</td>
<td>S.D.=0.1 GPa,Sb(+) 3.76e+14 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>2.300e+09</td>
<td>S.D.=0.2 GPa,Sb(+) 3.76e+15 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>1.900e+09</td>
<td>S.D.=0.6 GPa,Ge(+) 1.0e+15 cm[-2]</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>2.100e+09</td>
<td>S.D.=0.4 GPa,Ge(+) 1.0e+15 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>2.200e+09</td>
<td>S.D.=0.1 GPa,Ge(+) + B(+) 1.0e+15 cm[-2] + RTA</td>
</tr>
<tr>
<td>1.770e+04</td>
<td>1.900e+09</td>
<td>S.D.=0.4 GPa, RTA only</td>
</tr>
</tbody>
</table>

**Comments on Data**

Implantation followed by rapid thermal anneal(RTA) appears to enhance the fracture strength slightly.
Number of specimens was eight per test series.

**Reference**

FRACTURE OF SILICON WAFERS.
McLaughlin, J. C. Willoughby, A. F. W.
J. CRYST. GROWTH
Figure 221  Flexural Strength of Silicon, p-type
MATERIAL: Silicon

PROPERTY: Flexural Strength

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Wafers polished on both surfaces to a mirror-finish with silica gel.

Material Microstructure
Single crystalline material.

Panel/Billet/Lot/Batch Number
Lot 1

Specimen Identification
Number/Name: Lot 1, Series A and B specimens.
Additional Identifiers:
Wafer surface orientation was either (100) or (111).

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers
Parameters-Textual:
Circular aluminum platform had a 5 mm diameter hole with a slightly rounded edge to provide concentric support.
Load was transmitted to wafer by means of a spherical ball (ball diameter either 1.2 or 5.0 mm). Load was increased incrementally to fracture.
Flexure strength was calculated as the stress at fracture in the tensile surface using elastic bending theory.

Measured/Evaluated Properties
X : Temperature
Y : Flexural Strength

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>3.000e+09</td>
<td>S.D.=0.87 GPa,(100) Surface,1.2 mm Ball Radius</td>
</tr>
</tbody>
</table>
2.950e+02  3.100e+09  S.D.=1.4 GPa, (100) Surface, 5.0 mm Ball Radius
2.950e+02  2.100e+09  S.D.=0.8 GPa, (111) Surface, 1.2 mm Ball Radius
2.950e+02  2.800e+09  Standard Deviation Overall=1.2 GPa

Comments on Data
Ball diameter had no measurable effect on fracture strength.
Fracture strength for (100) surface is about 50 percent
higher than for (111) surface, but the statistical significance
is uncertain.
Presence of edge flaws was inconsequential for this test method.

Reference
CRITICAL STRESS IN SILICON BRITTLE FRACTURE, AND
EFFECT OF ION IMPLANTATION AND OTHER SURFACE
TREATMENTS.
Hu, S. M.
J. APPL. PHYS.
Figure 222  Flexural Strength of Silicon
Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Wafers were polished on both surfaces to a mirror-like finish
with silica gel.
Subsequent surface treatments:
Lot 1, Series A and B: control
Lot 1, Series C: quartz overlay
Lot 2, Series K: control
Lot 2, Series D: lapped with 12.5 micron alumina (4.5 micron
damage depth)
Lot 2, Series E: ground with 400 grit diamond (9 micron
damage depth)
Lot 2, Series F: ground with 1200 grit diamond (3 micron
damage depth)
Lot 2, Series G: ground with 1200 grit diamond (compression side)
Lot 2, Series H: polysilicon overlay (2 micron depth, 200 nm
grain size)
Lot 2, Series I: implantation with argon ions (150 keV,
1.0e+16 ions cm[-2] dosage)
Lot 2, Series J: implantation + anneal in nitrogen 1 hour
at 900 C
Lot 2, Series N: implantation + 2-step anneal
Lot 2, Series L: control + 2-step anneal

Material Microstructure
Single crystalline material.

Panel/Billet/Lot/Batch Number
Lots 1 and 2, each from a different ingot

Specimen Identification
Number/Name: Lot 1, Series A, B, and C.
Lot 2, Series D, E, F, G, H, I, J, K, L, and N
Orientation With Respect To Material: (100) Plane

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers

Parameters-Textual:
Circular aluminum platform had a 5 mm diameter hole with a
slightly rounded edge to provide concentric support.
Load was transmitted to wafer by means of a spherical ball (ball
diameter either 1.2 or 5.0 mm). Load was increased incrementally
to fracture.
Flexure strength was calculated as the stress at fracture
in the tensile surface using elastic bending theory.

Measured/Evaluated Properties
X : Temperature K
Y : Flexural Strength Pa

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>2.800e+09</td>
<td>S.D. = 1.2 GPa, Series A and B</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>2.400e+09</td>
<td>S.D. = 0.54 GPa, Series C</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.600e+09</td>
<td>S.D. = 0.65 GPa, Series K</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>3.300e+08</td>
<td>S.D. = 0.03 GPa, Series D</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>3.100e+08</td>
<td>S.D. = 0.05 GPa, Series E</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>4.000e+08</td>
<td>S.D. = 0.07 GPa, Series F</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.700e+09</td>
<td>S.D. = 0.14 GPa, Series G</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.300e+09</td>
<td>S.D. = 0.26 GPa, Series H</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.600e+09</td>
<td>S.D. = 0.8 GPa, Series I</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>2.300e+09</td>
<td>S.D. = 0.6 GPa, Series J</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.600e+09</td>
<td>S.D. = 0.6 GPa, Series N</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>1.500e+09</td>
<td>S.D. = 0.6 GPa, Series L</td>
</tr>
</tbody>
</table>

Comments on Data
Lot 1 had a total of 36 wafers while Lot 2 had 100.
Significant effects of surface preparation were observed
in the fracture strength.
A 5 mm radius ball was used for Lot 2 wafers.

Reference
CRITICAL STRESS IN SILICON BRITTLE FRACTURE, AND EFFECT OF ION IMPLANTATION AND OTHER SURFACE TREATMENTS.
Hu, S. M.
J. APPL. PHYS.
Figure 223 Flexural Strength of Silicon
Material Preparation
Crystal Growing Method:
Both Float-Zone and Czochralski methods.

Additional Preparation/Conditioning
Surface Treatment:
As-received wafers had one mirror finish surface (tension surface) and one deep etched surface (compression surface). The deep etched surface was heavily etched with CP4 (HF:HNO(3):glacial acetic acid = 3:5:3).

Material Microstructure
Float-zoned material contained significant bulk defects (uncharacterized) while the Czochralski material did not.

Specimen Identification
Number/Name: Float-zoned and Czochralski silicon
Orientation With Respect To Material: (100) Plane
Additional Identifiers:
Original wafer thicknesses were: 381 micron Float-Zoned.
Original wafer thicknesses were: 500 micron Czochralski.

Additional Properties
Other Properties-Textual:
Electrical Resistivity: 22-31 ohm cm for Float-Zoned.
Electrical Resistivity: 2-4 ohm cm for Czochralski.

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers
Circular aluminum platform had 5 mm diameter hole with a beveled edge to provide concentric support.
Load was applied by a 5 mm ball attached to an Instron machine.
Crosshead speed was 100 micron/min.
Fracture load was converted to flexure strength (tensile surface stress at fracture) using elastic bending theory.

Measured/Evaluated Properties
X : Depth Removed
Y : Flexural Strength
Z1 : Temperature

m
Pa
K

746
Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>3.700e+09</td>
<td>2.950e+02</td>
<td>FZ Silicon, 381 micron originally</td>
</tr>
<tr>
<td>7.700e-05</td>
<td>4.300e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>8.700e-05</td>
<td>4.400e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>1.200e-04</td>
<td>5.700e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>1.660e-04</td>
<td>8.800e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>1.040e-04</td>
<td>3.500e+09</td>
<td>2.950e+02</td>
<td>Czo. Silicon, 500 micron originally</td>
</tr>
<tr>
<td>1.860e-04</td>
<td>3.400e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>3.050e-04</td>
<td>4.600e+09</td>
<td>2.950e+02</td>
<td></td>
</tr>
</tbody>
</table>

Comments on Data
Evidently the Czochralski silicon contains significant bulk defects that are unaffected by the compression surface etching.

Reference
FRACTURE OF SILICON WAFERS.
McLaughlin, J. C. Willoughby, A. F. W.
J. CRYST. GROWTH
Figure 224 Flexural Strength of Silicon
Additional Preparation/Conditioning
Surface Treatment:
The back surfaces of wafers were either lapped or ground prior
to being chemically etched.

Material Microstructure
Single-crystalline silicon

Specimen Identification
Number/Name: Semiconductor grade wafers.
Dimensions (Geometry):
- Thickness: 0.28 mm
- Width: 3.81 mm
- Length: 3.81 mm
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Ball-Breaker Flexure Test for Wafers
Parameters-Textual:
A square silicon chip was placed on a soft pad (17 sheets from
an adhesive paper pad) and loaded by pressure contact from a
teflon ball 7.25 mm in diameter. Maximum load was
approximately 90 N.
After each test the top sheet of paper was changed and the
teflon ball was rotated.
The fracture strength of the tension surface (backface of the
wafer) was calculated from elastic plate theory.
Crosshead speed was 0.02 mm/sec.

Measured/Evaluated Properties
- X: Depth Removed
- Y: Flexural Strength
- Z1: Probability of Fracture
- Z2: Temperature

Data Points:
<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000e+00</td>
<td>2.000e+07</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td>Lapped and Etched Silicon</td>
</tr>
<tr>
<td>1.300e-05</td>
<td>5.800e+07</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>2.900e-05</td>
<td>5.100e+07</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>4.100e-05</td>
<td>1.590e+08</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>5.200e-05</td>
<td>7.600e+07</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>6.400e-05</td>
<td>2.210e+08</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>8.100e-05</td>
<td>1.720e+08</td>
<td>1.000e-01</td>
<td>2.950e+02</td>
<td></td>
</tr>
</tbody>
</table>

| 0.000e+00 | 2.800e+07 | 5.000e-01 | 2.950e+02 |
| 1.300e-05 | 9.500e+07 | 5.000e-01 | 2.950e+02 |
| 2.900e-05 | 8.600e+07 | 5.000e-01 | 2.950e+02 |
| 4.100e-05 | 2.250e+08 | 5.000e-01 | 2.950e+02 |
| 5.200e-05 | 2.120e+08 | 5.000e-01 | 2.950e+02 |
| 6.400e-05 | 3.020e+08 | 5.000e-01 | 2.950e+02 |
| 8.100e-05 | 2.490e+08 | 5.000e-01 | 2.950e+02 |

| 0.000e+00 | 3.000e+07 | 9.000e-01 | 2.950e+02 |
| 1.300e-05 | 1.830e+08 | 9.000e-01 | 2.950e+02 |
| 2.900e-05 | 1.270e+08 | 9.000e-01 | 2.950e+02 |
| 4.100e-05 | 2.590e+08 | 9.000e-01 | 2.950e+02 |
| 5.200e-05 | 2.630e+08 | 9.000e-01 | 2.950e+02 |
| 6.400e-05 | 3.020e+08 | 9.000e-01 | 2.950e+02 |
| 8.100e-05 | 2.490e+08 | 9.000e-01 | 2.950e+02 |

| 0.000e+00 | 3.500e+07 | 1.000e-01 | 2.950e+02 |
| 1.300e-05 | 1.580e+08 | 1.000e-01 | 2.950e+02 |
| 2.500e-05 | 1.290e+08 | 1.000e-01 | 2.950e+02 |
| 5.600e-05 | 1.420e+08 | 1.000e-01 | 2.950e+02 |
| 1.050e-04 | 1.750e+08 | 1.000e-01 | 2.950e+02 |

| 0.000e+00 | 4.600e+07 | 5.000e-01 | 2.950e+02 |
| 1.300e-05 | 2.290e+08 | 5.000e-01 | 2.950e+02 |
| 2.500e-05 | 2.270e+08 | 5.000e-01 | 2.950e+02 |
| 5.600e-05 | 2.370e+08 | 5.000e-01 | 2.950e+02 |
| 1.050e-04 | 2.750e+08 | 5.000e-01 | 2.950e+02 |

Comments on Data
The test limit was 250 - 300 MPa, so that the highest strengths were not determined.
The tabulations were read from Figures 10 and 11 which incurred data point reading errors of +/- 0.4 micron etch depth and +/- 2 MPa fracture strength.
The data indicate that grinding damage can be removed by etching about 15 micron of material, while lapping damage is much more difficult to remove.
Microscopy (SEM) of low-stress fractured surfaces indicated that cracking was initiated at flaws that were either etch pits or scratches, typically 10 micron long and 1 micron wide,
that occurred after etching.

Reference
MEASUREMENT OF SILICON STRENGTH AS AFFECTED BY WAFER BACK PROCESSING.
Hawkins, G. Berg, H. Mahalingam, M.
Lewis, G. Lofgran, L.
INTERNATIONAL RELIABILITY PHYSICS, ANN. PROC.
IEEE, 25TH 1987
Figure 225 Flexural Strength of Silicon
MATERIAL:  Silicon
PROPERTY:  Flexural Strength

*******************************************************************************

Material Preparation
Crystal Growing Method:
Czochralski

Additional Preparation/Conditioning
Surface Treatment:
Wafers polished on both surfaces to a mirror-finish with silica gel.

Material Microstructure
Single crystalline material.

Panel/Billet/Lot/Batch Number
Lot 1

Specimen Identification
Number/Name: Lot 1 specimens
Orientation With Respect To Material: (100) Plane

Measurement/Evaluation Method
Name/Description:
Ball-and-Ring Flexure Test for Wafers
Parameters-Textual:
Circular aluminum platform had a 5 mm diameter hole with a slightly rounded edge to provide concentric support.
Load was transmitted to wafer by means of a spherical ball (ball diameter either 1.2 or 5.0 mm). Load was increased incrementally to fracture.
Flexure strength was calculated as the stress at fracture in the tensile surface using elastic bending theory.

Measured/Evaluated Properties
X: Number of Occurrences
Y: Flexural Strength
Z1: Temperature

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
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<tr>
<td>0.000e+00</td>
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</tr>
<tr>
<td>0.000e+00</td>
<td>5.000e+08</td>
<td>2.950e+02</td>
</tr>
</tbody>
</table>

753
7.000e+00  1.000e+09  2.950e+02
1.100e+01  1.500e+09  2.950e+02
1.500e+01  2.000e+09  2.950e+02
1.500e+01  2.500e+09  2.950e+02
8.000e+00  3.000e+09  2.950e+02
8.000e+00  3.500e+09  2.950e+02
2.000e+00  4.000e+09  2.950e+02
4.000e+00  4.500e+09  2.950e+02
0.000e+00  5.000e+09  2.950e+02
0.000e+00  6.000e+09  2.950e+02
2.000e+00  6.500e+09  2.950e+02

Comments on Data
Tabulations are a histogram of fracture strength occurrences in intervals of 0.5 GPa lying above the tabulated strength value.

Reference
CRITICAL STRESS IN SILICON BRITTLE FRACTURE, AND EFFECT OF ION IMPLANTATION AND OTHER SURFACE TREATMENTS.
Hu, S. M.
J. APPL. PHYS.
Figure 226  Flexural Strength of Silicon
MATERIAL: Silicon: B doped

PROPERTY: Flexural Strength, Yield

Vendor/Producer/Fabricator
Mitsubishi Electric Corp.

Material Preparation
Crystal Growing Method:
Czochralski-grown crystals

Specimen Identification
Dimensions (Geometry):
Length 32. mm
Width 5.0 mm
Thickness 0.53 mm
Orientation With Respect To Material: [110] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 15-25 Ω cm
Temperature 298. K

Other Properties-Numerical:
Oxygen Concentration 11.5e17 cm⁻³
Temperature 298. K

Measurement/Evaluation Method
Name/Description:
Four-Point Bend Test
Parameters-Textual:
Four-point loading device made of quartz and the distances between inner and outer knife-edges are 8 and 24 mm, respectively.
The device was attached to an Instron machine.
Parameters-Codified:
Strain Rate: 1.5e-06 s⁻¹

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength, Yield Pa

Data Points:

X       Y
9.800e+02  8.840e+07
1.028e+03  6.400e+07
1.076e+03  4.370e+07

**Comments on Data**
Data was digitized from figure 2
yield strength of the as-received CZ-wafers decreases
monotonously with T.

**Reference**
MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON
WAFERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.
Yasutake, K.  Murakami, J.  Umeno, M.
Kawabe, H.
JPN. J. APPL. PHYS., PART 2
Figure 227 Flexural Strength, Yield of Silicon: B doped
**MATERIAL:** Silicon: B doped

**PROPERTY:** Flexural Strength, Yield

**Vendor/Producer/Fabricator**
Mitsubishi Electric Corp.

**Material Preparation**
Crystal Growing Method:
Floating-zone-grown crystals.

**Specimen Identification**
Dimensions (Geometry):
- Length: 32. mm
- Width: 5.0 mm
- Thickness: 0.53 mm
Orientation With Respect To Material: [110] Direction

**Additional Properties**
Electrical Properties:
- Electrical Resistivity: 15-25 Ω cm
- Temperature: 298. K

**Measurement/Evaluation Method**
Name/Description:
Four-Point Bend Test
Parameters-Textual:
Four-point loading device made of quartz and the distances between inner and outer knife-edges are 8 and 24 mm, respectively.
The device was attached to an Instron machine.
Parameters-Codified:
Strain Rate: 1.5e-06 s[-1]

**Measured/Evaluated Properties**
- X: Temperature K
- Y: Flexural Strength, Yield Pa

**Data Points**:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
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<tr>
<td>9.280e+02</td>
<td>1.593e+08</td>
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<tr>
<td>9.800e+02</td>
<td>9.380e+07</td>
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<tr>
<td>1.028e+03</td>
<td>6.040e+07</td>
</tr>
<tr>
<td>1.076e+03</td>
<td>5.370e+07</td>
</tr>
</tbody>
</table>
Comments on Data
Data was digitized from figure 2
Yield strength of the as-received FZ-wafers decreases
monotonously with T.

Reference
MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON
WAVERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.
Yasutake, K. Murakami, J. Umeno, M.
Kawabe, H.
JPN. J. APPL. PHYS., PART 2
Figure 228  Flexural Strength, Yield of Silicon: B doped
MATERIAL: Silicon: B doped

PROPERTY: Flexural Strength, Yield

********************************************************************************

Vendor/Producer/Fabricator
Mitsubishi Electric Corp.

Material Preparation
Crystal Growing Method:
Czochralski-grown crystals
Descriptors-Textual:
Chemically ploished and then annealed at 1073 K for 100 hrs.

Specimen Identification
Dimensions (Geometry):
Length 32. mm
Width 5.0 mm
Thickness 0.53 mm
Orientation With Respect To Material: [110] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 15-25 Ω cm
Temperature 298. K
Other Properties-Textual:
Etch pit density: approx. 8.0e09 cm[-3]
SiO(2) precipitate size: approx. 4200 Angstroms.

Measurement/Evaluation Method
Name/Description:
Four-Point Bend Test
Parameters-Textual:
Four-point loading device made of quartz and the distances between inner and outer knife-edges are 8 and 24 mm, respectively.
The device was attached to an Instron machine.
Parameters-Codified:
Strain Rate: 1.5e-06 s[-1]

Measured/Evaluated Properties
X: Temperature K
Y: Flexural Strength, Yield Pa

Data Points:
\begin{align*}
X  & \quad Y \\
7.960e+02 & 3.845e+08 \\
8.120e+02 & 3.627e+08 \\
8.200e+02 & 3.130e+08 \\
8.280e+02 & 2.546e+08 \\
8.600e+02 & 2.073e+08 \\
8.760e+02 & 1.638e+08 \\
9.280e+02 & 1.023e+08 \\
9.760e+02 & 7.190e+07 \\
1.028e+03 & 4.490e+07 \\
1.076e+03 & 3.350e+07
\end{align*}

**Comments on Data**

Data was digitized from figure 2.

Yield strength of wafers at 973 K are remarkably lowered by heat treatment. Plate-like SiO(2) precipitates of about 10.10 cm[-3] are observed by TEM and etch-pit method, but no punched-out dislocation loops exist. Annealed CZ wafers become ductile at T above 793 K.

**Reference**

MECHANICAL PROPERTIES OF HEAT-TREATED CZ-SILICON WAFERS FROM BRITTLE TO DUCTILE TEMPERATURE RANGE.

Yasutake, K. Murakami, J. Umeno, M. Kawabe, H.

JPN. J. APPL. PHYS., PART 2

Figure 229  Flexural Strength, Yield of Silicon: B doped
Material Preparation
Crystal Growing Method:
  Floating-Zone (FZ)

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
  Specimens were chemically polished to remove surface damage
  prior to indenting (CH(3)COOH:HNO(3):HF (1:10:1))
  Precursor crack produced by Knoop diamond indentor at center
  of tensile surface and in (110) plane such that crack was
  oriented perpendicular to tensile stress. Indentation load
  varied from 50 to 500g.
  Pre-cracked specimens were annealed in a quartz furnace at 700 °C
  under vacuum of 2.6e-04 Pa.

Material Microstructure
Dislocation-free 100 mm diameter (001) wafers
Interstitial oxygen (infra-red absorption): 1.0e+16 cm^-3
in FZ crystals.
Substitutional carbon content was below instrumental detection limit

Specimen Identification
Dimensions (Geometry):
  Length: 32 mm
  Width: 4 mm
  Thickness: 0.5 mm
Orientation With Respect To Material: [110] Direction

Additional Properties
Electrical Properties:
  Electrical Resistivity: 17-23 Ω cm
  Temperature: 295 K

Measurement/Evaluation Method
Name/Description:
  Four-Point Bend Test on Pre-Cracked Specimens
  Instron machine (Model TTCM-L) fixture has stainless steel
  sample supports separated by 25mm (outer) and 10mm (inner).
  The fracture stress on the outermost (tensile) surface was
  computed by simple elastic beam theory.
Parameters-Codified:
Cross-Head Speed : 0.02 mm min\(^{-1}\)

**Measured/Evaluated Properties**

\( X \) : Temperature \( K \)
\( Y \) : Fracture Toughness, Plane-Strain \( K(\text{Ic}) \) \( \text{Pa m}^{1/2}\)

Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks:} \\
2.950e+02 & 9.100e+05 & \text{S.D. = 0.09 MPa m}[1/2], (110) \text{ Crack Plane}
\end{array}
\]

**Comments on Data**

Approximately 30 specimens having varying pre-cracked lengths were measured and averaged together.
SEM profiles of the fracture surface indicate a semi-elliptical precursor crack and no stable crack growth.
Vacuum annealing evidently releases residual stresses around the precursor crack which would otherwise act as a driving force for crack extension.
Alternatively, annealing in air or oxygen was found to heal precursor cracks and increase fracture strength.
No appreciable difference between CZ and FZ material was observed.

**Reference**

CRACK HEALING AND FRACTURE STRENGTH OF SILICON CRYSTALS.
Yasutake, K. Iwata, M. Yoshii, K.
Umemo, M. Kawabe, H.
J. MATER. SCI.
21 (6), 2185-92, 1986.
Figure 230 Fracture Toughness, Plane-Strain $K(Ic)$ of Silicon: B dopes
MATERIAL: Silicon: B doped

PROPERTY: Fracture Toughness, Plane-Strain K(Ic)

Material Preparation
Crystal Growing Method:
Floating-Zone (FZ)

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Specimens were chemically polished to remove surface damage prior to indenting (CH(3)COOH:HNO(3):HF (1:10:1))
Precursor crack produced by Knoop diamond indentor at center of tensile surface and in (110) plane such that crack was oriented perpendicular to tensile stress. Indentation load varied from 50 to 500g.
Pre-cracked specimens were annealed in a quartz furnace at 700 C under vacuum of 2.6e-04 Pa.

Material Microstructure
Dislocation-free 100 mm diameter (001) wafers
Interstitial oxygen (infra-red absorption): 1.0e+16 cm[-3]
in FZ crystals.
Substitutional carbon content was below instrumental detection limit

Specimen Identification
Dimensions (Geometry):
Length 32  mm
Width 4  mm
Thickness 0.5  mm
Orientation With Respect To Material: [100] Direction

Additional Properties
Electrical Properties:
Electrical Resistivity 17-23  Ω cm
Temperature 295  K

Measurement/Evaluation Method
Name/Description:
Four-Point Bend Test on Pre-Cracked Specimens
Instron machine (Model TTCM-L) fixture has stainless steel sample supports separated by 25mm (outer) and 10mm (inner).
The fracture stress on the outermost (tensile) surface was computed by simple elastic beam theory.
Parameters-Codified:
Cross-Head Speed: 0.02mm min[-1]

**Measured/Evaluated Properties**

\[
\begin{align*}
X & : \text{Temperature} \\
Y & : \text{Fracture Toughness, Plane-Strain } K(\text{Ic}) \\
& \text{K Pa m}^{1/2}
\end{align*}
\]

Data Points:

\[
\begin{align*}
X & : 2.950e+02 \\
Y & : 9.500e+05 \\
& \text{S.D. = 0.10 MPa m}[1/2], (100) \text{ Crack Plane}
\end{align*}
\]

**Comments on Data**

Approximately 30 specimens having varying pre-cracked lengths were measured and averaged together.

SEM profiles of the fracture surface indicate a semi-elliptical precursor crack and no stable crack growth.

Vacuum annealing evidently releases residual stresses around the precursor crack which would otherwise act as a driving force for crack extension.

Alternatively, annealing in air or oxygen was found to heal precursor cracks and increase fracture strength.

No appreciable difference between CZ and FZ material was observed.

**Reference**

CRACK HEALING AND FRACTURE STRENGTH OF SILICON CRYSTALS.

Yasutake, K.  Iwata, M.  Yoshii, K.
Umeno, M.  Kawabe, H.
J. MATER. SCI.
21 (6), 2185-92, 1986.
Figure 231 Fracture Toughness, Plane-Strain $K_{IC}$ of Silicon: B doped
**Additional Preparation/Conditioning**
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Precursor cracks at the notch root of double cantilever beam specimens were propagated from a scratch by slowly forcing a wedge into the open notch while simultaneously applying a compressive stress across the crack plane. Precursor crack region was found to be free of dislocations by x-ray topography.
Surface Treatment:
Superficial machining abrasions were removed by chemical polishing

**Material Microstructure**
Single-crystalline material, ingot growth along <111>, p-type

**Specimen Identification**
Number/Name: Precracked Double-Cantilever Beam Specimen
Orientation With Respect To Material: [110] Direction
Additional Identifiers:
Double cantilever specimen was shaped like a truncated triangle.
Dimensions: base of triangle = 18.0 mm
height of triangle = 30.0 mm
width of truncated top = 5.3 mm
length of notch from top = 10.0 mm
holes for loading fixture had diameters of 1.0 mm, separation of 3.0 mm, and positions 1.5 mm from top

**Additional Properties**
Electrical Properties:
Electrical Resistivity 43 $\Omega$ cm
Temperature 295 K

**Measurement/Evaluation Method**
Name/Description:
Double Cantilever Beam with Pre-Cracked Specimen
Loading applied in a crack-opening orientation and with displacement speed of 5 to 500 micron/min.
Carefully taken load-deflection curve data indicated repeated (up to 8 in number) crack-initiation, propagation, and arrest features. Careful examination by interference microscopy allowed
precise crack-length measurement to be made. Data were analysed by applying existing critical stress intensity theory for this type of specimen.

**Measured/Evaluated Properties**

- **X**: Temperature
- **Y**: Fracture Toughness, Plane-Strain $K_{IC}$
- **Z1**: Cross-Head Speed

**Data Points**:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.715e+01</td>
<td>9.400e+05</td>
<td>8.333e-08</td>
<td>(111) Crack Planes</td>
</tr>
<tr>
<td>2.951e+02</td>
<td>9.370e+05</td>
<td>8.333e-08</td>
<td>Stand. Dev. = 0.052 MPa m[1/2]</td>
</tr>
<tr>
<td>9.782e+02</td>
<td>1.000e+06</td>
<td>8.333e-08</td>
<td>Approx. extrapolated</td>
</tr>
<tr>
<td>1.008e+03</td>
<td>1.000e+06</td>
<td>1.667e-07</td>
<td></td>
</tr>
<tr>
<td>1.076e+03</td>
<td>1.000e+06</td>
<td>8.333e-07</td>
<td></td>
</tr>
<tr>
<td>1.128e+03</td>
<td>1.000e+06</td>
<td>1.667e-06</td>
<td></td>
</tr>
<tr>
<td>1.210e+03</td>
<td>1.000e+06</td>
<td>8.333e-06</td>
<td></td>
</tr>
</tbody>
</table>

**Comments on Data**

Ductile-to-brittle transition is between 1074 and 1078 K for 50 micron/min cross-head speed. The extrapolations were made from a few data points just below the ductile-to-brittle transition for each cross-head speed. The fracture toughness was found to be essentially temperature and rate independent.

**Reference**

THE BRITTLE-TO-DUCTILE TRANSITION IN PRE-CLEAVED SILICON SINGLE CRYSTALS.

St. John, C.

PHILOS. MAG.

Figure 232 Fracture Toughness, Plane-Strain $K_{IC}$ of Silicon: B doperc
MATERIAL: Silicon

PROPERTY: Fracture Toughness, Plane-Strain K(Ic) DATA SET 233

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Indentation was produced by a Vickers pyramid indentor at a load of 30N. Indent occurred at the center of a face, with radial cracks aligned parallel to the edges.

Material Microstructure
Single crystal slices having (111) surfaces

Specimen Identification
Dimensions (Geometry):
Thickness 1 mm
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Indentation Fracture Method For Fracture Toughness
Indentation site was at center of tension face.
Existing theory of radial crack growth due to indentation stress field was applied to the crack system analysis.
Crack length used for each indentation was averaged over the four radial traces produced by the pyramid indentor.
The computation for fracture toughness required elastic modulus (E) and hardness (Vickers used here) data as input. Literature values used were E=168GPa and H=9.0GPa.

Experimental Conditioning/Material Degradation
Conditioning/Degradation/Environment: Air Environment

Measured/Evaluated Properties
X : Temperature
Y : Fracture Toughness, Plane-Strain K(Ic)

K Pa m$^{1/2}$

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>7.600e+05</td>
<td>Standard Deviation = 0.19 MPa m[1/2]</td>
</tr>
</tbody>
</table>

Comments on Data
Crack surfaces were perpendicular to specimen surface (111).
Reference
MECHANICS OF STRENGTH-DEGRADING CONTACT FLAWS IN SILICON.
Lawn, B. R. Marshall, D. B. Chantikul, P.
J. MATER. SCI.
16 (7), 1769-75, 1981.
Figure 233  Fracture Toughness, Plane-Strain $K(Ic)$ of Silicon
MATERIAL: Silicon

PROPERTY: Fracture Toughness, Plane-Strain K(Ic)

Material Microstructure
Single Crystal with dislocation density less than 1.0e+03 cm[-2]

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Microindentation Followed by Loading to Fracture

Measured/Evaluated Properties
X : Temperature
Y : Fracture Toughness, Plane-Strain K(Ic)

K Pa m^{1/2}

Data Points:

\[
\begin{array}{cc}
X & Y \\
2.930e+02 & 1.320e+06 \\
4.800e+02 & 1.300e+06 \\
6.730e+02 & 9.200e+05 \\
8.730e+02 & 8.600e+05 \\
9.730e+02 & 8.800e+05 \\
\end{array}
\]

Comments on Data
Elevated temperature tabulations were read from Figure 2.

Reference
INFLUENCE OF TEMPERATURE ON THE FAILURE OF BRITTLE MATERIALS IN CONCENTRATED LOADING.
Grigor'ev, O. N. Trefilov, V. I.
Shatokhin, A. M.
POROSHK. METALL.
22 (12), 75-82, 1983.
( FOR ENGLISH TRANSLATION SEE SOV. POWDER METALL.
MET. CERAM., 22 (12 ), 1028-33, 1983 )
Figure 234 Fracture Toughness, Plane-Strain $K_{IC}$ of Silicon
MATERIAL: Silicon

PROPERTY: Fracture Toughness, Plane-Strain K(\textit{Ic})

Vendor/Producer/Fabricator
Texas Instruments

Material Product Form:
Prepolished semiconductor grade single crystal.

Specimen Identification
Number/Name: Su101
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Indentation Fracture Method For Fracture Toughness
Under ambient conditions, the load dependence of both radial and diagonal cracks was measured. Crack lengths were measured along the surface around the indentations.
The expected crack planes include (110) planes normal to the (111) surface. Their traces perpendicular to the sample surface lie along \(<121>\).
Existing theory of radial crack growth due to indentation stress fields was applied. Literature values of tensile modulus and (Vickers) hardness were used to calculate fracture toughness.

Measured/Evaluated Properties
\(X\) : Temperature
\(Y\) : Fracture Toughness, Plane-Strain K(\textit{Ic})

\(K\) Pa m\(^{1/2}\)

Data Points:

\[
\begin{array}{ccc}
X & Y & \text{Remarks:} \\
2.950e+02 & 7.440e+05 & 2N Indentor Load \\
2.950e+02 & 8.860e+05 & 5N Indentor Load \\
\end{array}
\]

Comments on Data
Five samples were measured for each load.

Reference
CHANGING THE SURFACE MECHANICAL PROPERTIES OF SILICON AND ALPHA-ALUMINUM OXIDE BY ION IMPLANTATION.
Burnett, P. J. Page, T. F.
J. MATER. SCI.
Figure 235 Fracture Toughness, Plane-Strain $K(1c)$ of Silicon
Material Preparation
Crystal Growing Method:
Czochralski grown, 4 cm diameter ingot

Additional Preparation/Conditioning
Surface Treatment:
One surface was polished to mirror-like finish with 0.05 micron alumina (Linde B) as the final abrasive.

Material Microstructure
Dislocation-free material

Specimen Identification
Orientation With Respect To Material: (111) Plane

Measurement/Evaluation Method
Name/Description:
Microindentation and Crack-System Analysis
Microindentation achieved in ambient air with a Vickers diamond indenter under loads of 2 to 5 N.
Parameters-Textual:
Crack pattern formed was two virtually orthogonal semicircular cracks along (110) and (112) planes, perpendicular to the (111) specimen surface.
Characteristic dimensions of surface cracks were measured with a tracking microscope.
The theoretical model applied toward the analysis is well established.

Measured/Evaluated Properties
X: Temperature
Y: Fracture Toughness, Plane-Strain K(Ic)

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>1.000e+06</td>
<td>Standard Deviation = 0.08 MPa m[1/2]</td>
</tr>
</tbody>
</table>

Comments on Data
Number of specimens tested was at least 20.
Crack surfaces were (110) and (112) planes.
No evidence of environmental influences on crack resistance was observed.

Reference
MICROINDENTATION FOR FRACTURE AND STRESS-CORROSION CRACKING STUDIES IN SINGLE-CRYSTAL SILICON.
Wong, B. Holbrook, R. J.
J. ELECTROCHEM. SOC.
134 (9), 2254-6, 1987.
Figure 236 Fracture Toughness, Plane-Strain K(Ic) of Silicon
**Material Preparation**
Crystal Growing Method:
Directional solidification casting

**Additional Preparation/Conditioning**
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Precursor cracks produced by Vickers indenter under 20N load
directed into the tensile surface with indenter axes parallel
to sample edges.
Flaw lengths were measured with SEM on fractured surfaces.

**Material Microstructure**
Grain Sizes: 0.3 to 3 mm perpendicular to growth direction
1 to 10 mm parallel to growth direction

**Specimen Identification**
Number/Name: Directionally Cast Polycrystalline Silicon
Dimensions (Geometry):

<table>
<thead>
<tr>
<th>Length</th>
<th>50.8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>2.74 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>6.04 mm</td>
</tr>
</tbody>
</table>

Orientation With Respect To Material: Transverse Direction in T-L Plane

**Measurement/Evaluation Method**
Name/Description:
Four-Point Flexural Test on Pre-Indented Specimens
Major span distance was 40 mm and minor span was 19 mm

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>8.200e+05</td>
<td>6.560e+07</td>
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<tr>
<td>2.950e+02</td>
<td>9.700e+05</td>
<td>8.620e+07</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>9.600e+05</td>
<td>6.600e+07</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>7.400e+05</td>
<td>7.140e+07</td>
</tr>
</tbody>
</table>

Remarks:
2.950e+02  8.500e+05  7.950e+07

2.950e+02  8.700e+05  Average:  Stand. Dev. = 11.2 %

**Comments on Data**
Crack propagation is transverse to grains for this orientation. Since flaw size (typically 0.2 mm) is smaller than grain size these fracture toughness results are not much different from single-crystalline silicon data.

**Reference**
FRACTURE OF DIRECTIONALLY SOLIDIFIED MULTICRYSTALLINE SILICON.
Chen, C. P.  Leipold, M. H., Jr.
Helmreich, D.
J. AM. CERAM. SOC.
65, C-49, 1982.
Figure 237 Fracture Toughness, Plane-Strain $K(Ic)$ of Silicon
Material Preparation
Crystal Growing Method:
Directional solidification casting

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Precursor cracks produced by Vickers indentor under 20N load
directed into the tensile surface with indentor axes parallel
to sample edges.
Flaw lengths were measured with SEM on fractured surfaces.

Material Microstructure
Grain Sizes: 0.3 to 3 mm perpendicular to growth direction
1 to 10 mm parallel to growth direction

Specimen Identification
Number/Name: Directionally Cast Polycrystalline Silicon
Dimensions (Geometry):
Length: 50.8 mm
Width: 5.98 mm
Thickness: 3.00 mm
Orientation With Respect To Material: Transverse Direction in T-S Plane

Measurement/Evaluation Method
Name/Description:
Four-Point Flexural Test on Pre-Indented Specimens
Major span distance was 40 mm and minor span was 19 mm

Measured/Evaluated Properties
X: Temperature
Y: Fracture Toughness, Plane-Strain K(Ic)
Z1: Flexural Strength

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
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<td>8.810e+07</td>
<td>5 N Vickers indentor</td>
</tr>
<tr>
<td>2.950e+02</td>
<td>9.100e+05</td>
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<td>2.950e+02</td>
<td>6.700e+05</td>
<td>4.950e+07</td>
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<tr>
<td>2.950e+02</td>
<td>7.400e+05</td>
<td>6.940e+07</td>
<td></td>
</tr>
</tbody>
</table>
2.950e+02  9.900e+05  7.520e+07
2.950e+02  8.000e+05  Average: Stand Dev. = 17.7 %

Comments on Data
Crack propagation is along grains for this orientation. Since flaw size (typically 0.3 mm) is no larger than grain sizes, these fracture toughness results do not differ appreciably from single-crystalline silicon data.

Reference
FRACUTRE OF DIRECTIONALLY SOLIFIED MULTICRYSTALLINE SILICON.
Chen, C. P. Leipold, M. H., Jr.
Helmreich, D.
J. AM. CERAM. SOC.
65, C-49, 1982.
Material Preparation

Crystal Growing Method:
Czochralski, with ingot grown in <111> direction

Material Microstructure
Single-crystalline material

Specimen Identification
Orientation With Respect To Material: [111] Direction

Measurement/Evaluation Method

Name/Description:
Four-Point Flexure on Notched Specimen (Notch-Root Radius Effect)

Parameters-Textual:
Major span distance was 10.16 cm and minor span was 5.08 cm

Measured/Evaluated Properties

X: Radius of Notch Tip (Root Radius)
Y: Stress Intensity at Fracture
Z1: Flexural Strength
Z2: Temperature

Data Points:

<table>
<thead>
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<th>X</th>
<th>Y</th>
<th>Z1</th>
<th>Z2</th>
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<tr>
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</tr>
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<td>2.950e+02</td>
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</tr>
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</tr>
<tr>
<td>1.300e-04</td>
<td>1.240e+06</td>
<td>2.950e+02</td>
<td></td>
</tr>
<tr>
<td>1.500e-04</td>
<td>1.570e+06</td>
<td>1.180e+08</td>
<td>2.950e+02</td>
</tr>
<tr>
<td>1.500e-04</td>
<td>2.010e+06</td>
<td>1.500e+08</td>
<td>2.950e+02</td>
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<tr>
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</tr>
<tr>
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<td>1.810e+06</td>
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<td></td>
</tr>
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<tr>
<td>5.600e-04</td>
<td>2.560e+06</td>
<td>1.170e+08</td>
<td>2.950e+02</td>
</tr>
<tr>
<td>5.600e-04</td>
<td>2.410e+06</td>
<td>1.100e+08</td>
<td>2.950e+02</td>
</tr>
<tr>
<td>5.800e-04</td>
<td>2.850e+06</td>
<td>1.300e+08</td>
<td>2.950e+02</td>
</tr>
</tbody>
</table>

Comments on Data
Average flexural strength was 128 MPa.
Stress intensity for small notch-root radius compares favorably
with published fracture toughness data for silicon measured
by blunt-notch indentation methods.

Reference
EFFECT OF NOTCH ROOT RADIUS ON THE FRACTURE BEHAVIOUR
OF MONOCRYSTALLINE SILICON.
Myers, R. J.  Hillberry, B. M.
FRACTURE 1977, ADVANCE IN RESEARCH ON THE STRENGTH
AND FRACTURE OF MATERIALS, VOL. 3B-APPLICATIONS AND
NON-METALS, INT. CONF. FRACTURE, ICF4
(Edited by D. M. R. Taplin; Pergamon Press: New
York)
Figure 239 Stress Intensity at Fracture of Silicon
MATERIAL: Silicon: P doped

PROPERTY: Surface Energy for Cleavage

Vendor/Producer/Fabricator
Philsip Laboratories, North American Philips Corporation

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
The as-received 0.2 cm thick slabs had previously been polished to device-grade standards.
Specimens were cut with a diamond saw, polished, and etched to remove cutting damage.
Precursor cracks were produced by a spark discharge. Due to the high resistivity of silicon a silver film 1000 Angstroms thick was vapor-deposited to enable the spark discharge to occur. No evidence was observed for the presence of silver in the crater or precursor cracks as determined by microprobe analysis.

Material Microstructure
Single-crystalline material with dislocation density < 200 cm[-2].

Specimen Identification
Dimensions (Geometry):
- Length: 15 mm
- Width: 5 mm
- Thickness: 2 mm
Orientation With Respect To Material: (110) Plane

Additional Properties
Electrical Properties:
- Electrical Resistivity: 0.14 Ω cm
- Temperature: 295 K

Measurement/Evaluation Method
Name/Description:
- Tensile Fracture of Pre-Cracked Specimens
Precursor crack length on fracture surface was measured optically by using Nomarski interference contrast to highlight the crack front.
Parameters-Textual:
- Instrom machine was employed with cross-head speed of 0.127 cm/min.

Measured/Evaluated Properties
X : Temperature  
Y : Surface Energy for Cleavage

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.930e+02</td>
<td>1.140e+00</td>
<td>Stand. Dev. = 0.15, (111) Crack Surfaces</td>
</tr>
</tbody>
</table>

**Comments on Data**
Fracture strength versus precursor-crack length for seven specimens was used to compute the surface cleavage energy for (111) crack surfaces.
The evidence indicated that the stress field at the precursor crack tip satisfied the Griffith criterion.

**Reference**
THE SURFACE ENERGY OF SILICON, GALLIUM ARSENIDE, AND GALLIUM PHOSPHIDE.
Messmer, C. Bilello, J. C.
J. APPL. PHYS.
52 (7), 4623-9, 1981.
Figure 240  Surface Energy for Cleavage of Silicon: P doped
MATERIAL: Silicon: P doped

PROPERTY: Surface Energy for Cleavage

**********

Vendor/Producer/Fabricator
Philips Laboratories, North American Philips Corporation

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
The as-received 0.2 cm thick slabs had previously been polished to device-grade standards.
Specimens were cut with a diamond saw, polished, and etched to remove cutting damage.
Precursor cracks were produced by a spark discharge. Due to the high resistivity of silicon a silver film 1000 Angstroms thick was vapor-deposited to enable the spark discharge to occur. No evidence was observed for the presence of silver in the crater or precursor cracks as determined by microprobe analysis.

Material Microstructure
Single-crystalline material with dislocation density < 200 cm[-2].

Specimen Identification
Dimensions (Geometry):
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>15</td>
<td>mm</td>
</tr>
<tr>
<td>Width</td>
<td>5</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>2</td>
<td>mm</td>
</tr>
</tbody>
</table>
Orientation With Respect To Material: (111) Plane

Additional Properties
Electrical Properties:
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Resistivity</td>
<td>0.14</td>
</tr>
<tr>
<td>Temperature</td>
<td>295</td>
</tr>
</tbody>
</table>

Measurement/Evaluation Method
Name/Description:
Tensile Fracture of Pre-Cracked Specimens
Precursor crack length on fracture surface was measured optically by using Nomarski interference contrast to highlight the crack front.
Parameters-Textual:
Instrom machine was employed with cross-head speed of 0.127 cm/min.

Measured/Evaluated Properties
X : Temperature \( K \)  
Y : Surface Energy for Cleavage \( J \ m^{-2} \)

Data Points :

\[
\begin{array}{ccc}
X & Y & 
\text{Remarks:} \\
2.930e+02 & 1.900e+00 & \text{Stand. Dev.} = 0.20, (110) \text{ Crack Surfaces}
\end{array}
\]

**Comments on Data**
Fracture strength versus precursor-crack length for six specimens was averaged to compute the surface cleavage energy for (110) crack surfaces.
Evidence indicated that the Griffith criterion for stress field at the precursor-crack tip was satisfied.

**Reference**
THE SURFACE ENERGY OF SILICON, GALLIUM ARSENIDE, AND GALLIUM PHOSPHIDE.
Messmer, C.  Bilello, J. C.
J. APPL. PHYS.
52 (7), 4623-9, 1981.
Figure 241  Surface Energy for Cleavage of Silicon: P doped
MATERIAL: Silicon, n-type

PROPERTY: Surface Energy for Cleavage

**Vendor/Producer/Fabricator**
Monsanto Company, St. Louis, Mo.

**Additional Preparation/Conditioning**
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
As-cut specimens were lapped with 600 grit silicon carbide and subsequently etched.
Precursor cracks were produced by scribing lines on the flat faces of the specimens.
Precursor cracks from L/3 to 2L/3 in length (L = specimen length) resulted in compliance being proportional to crack length.

**Specimen Identification**
Number/Name: Double-Torsion Specimen
Dimensions (Geometry):
- Length: 25.4 mm
- Width: 6.4 mm
- Thickness: 0.38 mm
Additional Identifiers:
- Specimen flat faces were \{100\} planes
- Precursor crack planes were \{110\} planes

**Additional Properties**
Electrical Properties:
- Electrical Resistivity: 173+/-10 \(\Omega \cdot m\)
- Temperature: 295 \(K\)

**Measurement/Evaluation Method**
Name/Description: Double-Torsion Method
An Instron machine was fitted with a compression cage, a double torsion jig and a CM load cell.
Parameters-Textual:
- A cross-head speed of 0.127 mm s\(^{-1}\) was used.
- Crack length was measured by optical microscopy on cleaved surfaces and the orientation was determined by the Laue back reflection method.
- The theoretical model took elastic anisotropy into account.

**Measured/Evaluated Properties**
X : Temperature
Y : Surface Energy for Cleavage

Data Points :

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.950e+02</td>
<td>1.810e+00</td>
</tr>
</tbody>
</table>

Comments on Data
Fracture occurred in Mode I and was of type (110)[110].
The critical load value was 0.650 kg.
Critical stress intensity was 0.74 MN m[-3/2].
Critical energy release rate was 3.62 J m[-2].

Reference
FRACTURE SURFACE ENERGY DETERMINATION IN (110) PLANE IN SILICON BY THE DOUBLE TORSION METHOD.
Bhaduri, S. B. Wang, F. F. Y.
J. MATER. SCI.
Figure 242  Surface Energy for Cleavage of Silicon, n-type
MATERIAL: Silicon

PROPERTY: Surface Energy for Cleavage

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Polished and thinned slices were carefully cracked at one edge while rigidly clamping the slice.
Measurement specimen was cut from such a precracked slice.

Material Microstructure
Single-crystalline material

Measurement/Evaluation Method
Name/Description:
Double Cantilever Beam Using a Pre-Cracked Specimen
Tungsten-wire hooks were attached to each side of crack to apply force while the specimen was immersed into liquid nitrogen.
Parameters-Textual:
Loading was accomplished by adding links of a chain (1.7g/link) to the specimen.
Crack length was measured along the fracture surfaces using a traveling microscope.
Existing theory for double cantilever beams was used to analyse the data.

Measured/Evaluated Properties
X: Temperature
Y: Surface Energy for Cleavage

Data Points:

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.715e+01</td>
<td>1.220e+00</td>
<td>Specimen Number Si 2,(111) Crack Planes</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.230e+00</td>
<td>Si 14</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.230e+00</td>
<td>Si 15</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.230e+00</td>
<td>Si 6</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.235e+00</td>
<td>Si 10</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.240e+00</td>
<td>Si 12</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.250e+00</td>
<td>Si 5</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.245e+00</td>
<td>Si 9</td>
</tr>
<tr>
<td>7.715e+01</td>
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<td>Si 7</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.270e+00</td>
<td>Si 3</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.270e+00</td>
<td>Si 8</td>
</tr>
<tr>
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<td>----------------</td>
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<td>-------</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.270e+00</td>
<td>Si 13</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.280e+00</td>
<td>Si  4</td>
</tr>
<tr>
<td>7.715e+01</td>
<td>1.290e+00</td>
<td>Si 16</td>
</tr>
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<td>7.715e+01</td>
<td>1.300e+00</td>
<td>Si  1</td>
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<tr>
<td>7.715e+01</td>
<td>1.230e+00</td>
<td>Average for 15 specimens, (111) Crack Planes</td>
</tr>
</tbody>
</table>

**Comments on Data**
Since dissipative factors tended to increase the surface cleavage energy, any high values were excluded from the tabulations.
The crack surfaces were (111) planes in each case.

**Reference**
SURFACE ENERGY OF GERMANIUM AND SILICON.
Jaccodine, R. J.
J. ELECTROCHEM. SOC.
110 (6), 524-7, 1963.
Figure 243  Surface Energy for Cleavage of Silicon
MATERIAL: Silicon

PROPERTY: Surface Energy for Cleavage

Vendor/Producer/Fabricator
Semiconductor Products Department of General Electric Co.

Material Preparation
Crystal Growing Method:
Floating-zone

Additional Preparation/Conditioning
Conditioning/Preparation: Precursor Crack Generation
Descriptors-Textual:
Specimens were cut, slotted at one end, had holes bored for attachments, and chemically polished with HF + HNO(3).
Precursor crack was initiated by abrading the base of the slot.
Initial crack was started by using a knife blade jig immersed in liquid nitrogen.

Material Microstructure
Single crystals of semiconductor grade silicon

Specimen Identification
Number/Name: Specimen numbers S-10 and S-4.
Dimensions (Geometry):
- Length: 8.5 mm
- Width: 2.20 mm
- Thickness: 2.84 mm
- Length: 10.1 mm
- Width: 3.10 mm
- Thickness: 1.93 mm

Additional Identifiers:
Specimen sides (one set) were \{111\} planes
Specimen length was along \langle112\rangle.

Measurement/Evaluation Method
Name/Description:
Double Cantilever Beam Using a Pre-Cracked Specimen.
Parameters-Textual:
A specially designed yoke attached to the specimen by pivot bearings was used to transmit force to the specimen.
An Instron testing machine was used with load applied at a rate of 8 gram/sec.
Critical loads for crack propagation correspond to loads
for which the crack length suddenly increased by some amount. Crack length was measured by microscopic examination of the cleaved surfaces. Surface cleavage energy was obtained from a theoretical modeling of critical crack growth.

**Measured/Evaluated Properties**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>J m^{-2}</td>
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</tbody>
</table>

**Data Points:**

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.700e+01</td>
<td>1.250e+00</td>
<td>Specimen S-10</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>1.230e+00</td>
<td>Specimen S-4</td>
</tr>
<tr>
<td>7.700e+01</td>
<td>1.240e+00</td>
<td>Average Value</td>
</tr>
</tbody>
</table>

**Comments on Data**

Cleavage surfaces were \{111\} planes.

**Reference**

DIRECT MEASUREMENTS OF THE SURFACE ENERGIES OF CRYSTALS.
Gilman, J. J.
J. APPL. PHYS.
31 (12), 2208-18, 1960.
Figure 244  Surface Energy for Cleavage of Silicon
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