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X-ray photoelectron spectroscopy (XPS) was used to analyze a commercially available SrTiO₃(001) bulk single crystal. XP spectra were obtained using incident monochromatic Al Kα radiation at 0.83401 nm. A survey spectrum together with O 1s, Ti 2p, C 1s, Sr 3p, Sr 3d, Ti 3p, Sr 4p, Ti 3p, Ti 4p, and O 2s core level spectra and the valence band are presented. The spectra indicate the principle core level photoelectron and Auger electron signals and show only minor carbon contamination. Making use of the O 1s, Ti 2p, Sr 3d lines and neglecting the components related to surface contaminants, XPS quantitative analysis reveals an altered stoichiometry of the air-exposed crystal surface of Sr₁.₁₆TiO₂.₀₉. © 2014 American Vacuum Society.

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Keywords: strontium titanium oxide; perovskite

INTRODUCTION

Transition metal oxides present an impressive variety of functionality which is not available in more traditional systems such as group IV and III-V semiconductors or elemental metals. Among the many possible functionalities are, for instance, ferroelectricity (Ref. 1) and magnetism (Ref. 2), colloidal magnetoresistance (Ref. 3), and high temperature superconductivity (Ref. 4), with transport character ranging from insulating to semiconducting to metallic. Furthermore, these properties are extremely sensitive to perturbations from chemistry, structural defects, strain and many other effects and this, in turn, provides the materials engineer a number of routes by which to engineer new functionalities in this class of materials (Ref. 5).

While even simple oxide systems, such as binary oxides, exhibit a broad diversity of properties, it is the ternary systems which have received the most attention in recent years. In particular, materials possessing the perovskite structure (with chemical formula ABO₃) have been observed to exhibit an incredible variety of functionality and phenomena. Advances in thin film epitaxy, particularly pulsed laser deposition, RF magnetron sputtering, and molecular beam epitaxy, have enabled researchers to carefully tune material properties using epitaxial strain. Such approaches have provided an opportunity to apply large biaxial strains (as much as several percent in some cases) to nanoscale films of various materials which would lead to cracks in bulk materials under similar values of hydrostatic strain (Ref. 6).

SPECIMEN DESCRIPTION (ACCESSION #01310)

Host Material: Single crystal SrTiO₃
CAS Registry #: 1206-05-9
Host Material Characteristics: homogeneous; solid; single crystal; dielectric; inorganic compound
Chemical Name: Strontium titanium oxide
Source: Crystec, GmbH. Grown by the Verneuill method.
Host Composition: SrTiO₃
Form: single crystal
Structure: cubic, perovskite structure, a = 0.3905 nm (Ref. 7)

History & Significance: SrTiO₃ has been widely studied for its interesting properties and as a common substrate for epitaxial film growth. The static dielectric permittivity (εᵣ) of SrTiO₃ is ~300 at room temperature and rapidly increases upon cooling to values in excess of 20,000 in the quantum paraelectric state below 10K (Ref. 8). Likewise, SrTiO₃ has drawn attention as a candidate material for thermoelectrics based on its large carrier effective mass and resulting large thermopower (Ref. 9). More generally, SrTiO₃ is one of the most widely studied perovskite oxides and is highly susceptible to donor-doping by cationic substitution, oxygen vacancies, and field effects that result in a dramatic range of transport properties ranging from insulating to metallic to superconducting states (Ref. 10). In order to gain an increased understanding of the surfaces and hetero-interfaces of perovskite-based materials, a SrTiO₃(001) bulk single crystal was analyzed using X-ray photoelectron spectroscopy.
As Received Condition: as grown
Analyzed Region: same as host material

**Ex Situ Preparation/Mounting:** Samples were cleaned ultrasonically for 5 min each in Formula 409\textsuperscript{V}, methyl alcohol, and deionized water. Samples were mounted onto the sample holder using double-sided carbon tape (Pella product number 16074).

**In Situ Preparation:** None
**Pre-Analysis Beam Exposure:** Less than 2 min; no x-ray degradation effects observed
**Charge Control:** low energy flood gun/magnetic immersion lens combination, filament current = 2.1 A, charge balance = 2.1 V, filament bias = 2 V

**Temp. During Analysis:** 300 K
**Pressure During Analysis:** <3 \times 10^{-7} \text{ Pa}

**INSTRUMENT DESCRIPTION**

Manufacturer and Model: Kratos Axis Ultra
Analyzer Type: spherical sector
Detector: channeltron electron multiplier
Number of Detector Elements: 8

**INSTRUMENT PARAMETERS COMMON TO ALL SPECTRA**

- **Spectrometer**
  - Analyzer Mode: constant pass energy
  - Throughput (\( T = E^0 \)): \( N = 0 \)
  - Excitation Source Window: not specified
  - Excitation Source Energy: 1486.6 eV
  - Source Strength: 120 W
  - Source Beam Size: 2000 \( \mu \text{m} \times 2000 \mu \text{m} \)
  - Signal Mode: multichannel direct

- **Geometry**
  - Incident Angle: 54°
  - Source to Analyzer Angle: 54°
  - Emission Angle: 0°
  - Specimen Azimuthal Angle: 45°
  - Acceptance Angle from Analyzer Axis: 0°
  - Analyzer Angular Acceptance Width: 40° \times 40°

**DATA ANALYSIS METHOD**

Energy Scale Correction: The binding energy scale was referenced to C 1s = 285.0 eV.

**Recommended Energy Scale Shift:** +3.929 eV for high-resolution spectra

**Peak Shape and Background Method:** Background: Custom three parameter Tougaard background (Ref. 11), U 4 Tougaard (B, C, D, T0 = 0) (Ref. 12), was used. O 1s: B = 270 eV\textsuperscript{2}, C = 300 eV\textsuperscript{2}, D = 100 eV\textsuperscript{2}. Ti 2p: B = 230 eV\textsuperscript{2}, C = 300 eV\textsuperscript{2}, D = 100 eV\textsuperscript{2}. C 1s: B = 165 eV\textsuperscript{2}, C = 260 eV\textsuperscript{2}, D = 300 eV\textsuperscript{2}. Sr 3d: B = 230 eV\textsuperscript{2}, C = 300 eV\textsuperscript{2}, D = 100 eV\textsuperscript{2}.

**Quantitation Method:** Quantification was done using region and component definitions with CasaXPS version 2.3.15. Sensitivity factors supplied by Kratos Analytical. Errors are given as \( \pm 1 \) standard deviation. Standard deviations are calculated by CasaXPS using a Monte Carlo method for determining the error distribution for the computed areas.

**ACKNOWLEDGMENTS**

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**REFERENCES**

## SPECTRAL FEATURES TABLE

<table>
<thead>
<tr>
<th>Spectrum ID #</th>
<th>Element/Transition</th>
<th>Peak Energy (eV)</th>
<th>Peak Width FWHM (eV)</th>
<th>Peak Area (eV $\times$ cts/s)</th>
<th>Sensitivity Factor</th>
<th>Concentration (at. %)</th>
<th>Peak Assignment</th>
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<tbody>
<tr>
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<td>O 1s</td>
<td>529.5</td>
<td>1.07</td>
<td>16808.6</td>
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<td>35.45</td>
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<td>01310-04$^a$</td>
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<td>Sr 4p$_{1/2}$</td>
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<td>01310-07$^b$</td>
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</table>

$^a$ Result of exposure to air  
$^b$ O 2p and Ti 3d (Ref. 13)  
$^c$ O 2p (Ref. 13)  
$^d$ The position of VBM was estimated by subtracting 1/2 of the full width at half maximum (FWHM) from the position of the maximum intensity at the VBM.

## ANALYZER CALIBRATION TABLE

<table>
<thead>
<tr>
<th>Spectrum ID #</th>
<th>Element/Transition</th>
<th>Peak Energy (eV)</th>
<th>Peak Width FWHM (eV)</th>
<th>Peak Area (eV $\times$ cts/s)</th>
<th>Sensitivity Factor</th>
<th>Concentration (at. %)</th>
<th>Peak Assignment</th>
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<tbody>
<tr>
<td>Au 4f$_{7/2}$</td>
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<tr>
<td>Ag 3d$_{5/2}$</td>
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<td>0.58</td>
<td>230506.2</td>
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<tr>
<td>Cu 2p$_{3/2}$</td>
<td>932.6</td>
<td>0.88</td>
<td>410979.8</td>
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### GUIDE TO FIGURES

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<tr>
<th>Spectrum (Accession) #</th>
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<th>Voltage Shift</th>
<th>Multiplier</th>
<th>Baseline</th>
<th>Comment #</th>
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<td>0</td>
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<td>1310-03</td>
<td>Ti 2p</td>
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<tr>
<td>1310-04</td>
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<td>1310-05</td>
<td>Sr 3d</td>
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<td>1</td>
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<td>1310-06</td>
<td>Ti 3p</td>
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<tr>
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<td>Sr 4p, O 2s, valence band</td>
<td>−3.929</td>
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</tbody>
</table>

*Voltage shift of the archived (as-measured) spectrum relative to the printed figure. The figure reflects the recommended energy scale correction due to a calibration correction, sample charging, flood gun, or other phenomenon.*
<table>
<thead>
<tr>
<th><strong>Accession #</strong></th>
<th>01310–01</th>
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</thead>
<tbody>
<tr>
<td><strong>Host Material</strong></td>
<td>Single crystal SrTiO$_3$</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td>XPS</td>
</tr>
<tr>
<td><strong>Spectral Region</strong></td>
<td>survey</td>
</tr>
<tr>
<td><strong>Instrument</strong></td>
<td>Kratos Axis Ultra</td>
</tr>
<tr>
<td><strong>Excitation Source</strong></td>
<td>Al K$_a$ monochromatic</td>
</tr>
<tr>
<td><strong>Source Energy</strong></td>
<td>1486.6 eV</td>
</tr>
<tr>
<td><strong>Source Strength</strong></td>
<td>120 W</td>
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<tr>
<td><strong>Source Size</strong></td>
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<tr>
<td><strong>Analyzer Type</strong></td>
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<tr>
<td><strong>Incident Angle</strong></td>
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<td><strong>Emission Angle</strong></td>
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<tr>
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<tr>
<td><strong>Analyzer Resolution</strong></td>
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<tr>
<td><strong>Total Signal Accumulation Time</strong></td>
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<td><strong>Total Elapsed Time</strong></td>
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<tr>
<td><strong>Number of Scans</strong></td>
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<tr>
<td><strong>Effective Detector Width</strong></td>
<td>33.6 eV</td>
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*Surface Science Spectra, Vol. 21, 2014*
**Accession #: 01310–02**

**Host Material:** Single crystal SrTiO$_3$

**Technique:** XPS

**Spectral Region:** O 1s

- **Instrument:** Kratos Axis Ultra
- **Excitation Source:** Al K$_\alpha$, monochromatic
- **Source Energy:** 1486.6 eV
- **Source Strength:** 120 W
- **Source Size:** 2 mm x 2 mm
- **Analyzer Type:** spherical sector
- **Incident Angle:** 54°
- **Emission Angle:** 0°
- **Analyzer Pass Energy:** 20 eV
- **Analyzer Resolution:** 0.3 eV
- **Total Signal Accumulation Time:** 1508 s
- **Total Elapsed Time:** 4147 s
- **Number of Scans:** 25
- **Effective Detector Width:** 4.2 eV

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**Accession #: 01310–03**

**Host Material:** Single crystal SrTiO$_3$

**Technique:** XPS

**Spectral Region:** Ti 2p

- **Instrument:** Kratos Axis Ultra
- **Excitation Source:** Al K$_\alpha$, monochromatic
- **Source Energy:** 1486.6 eV
- **Source Strength:** 120 W
- **Source Size:** 2 mm x 2 mm
- **Analyzer Type:** spherical sector
- **Incident Angle:** 54°
- **Emission Angle:** 0°
- **Analyzer Pass Energy:** 20 eV
- **Analyzer Resolution:** 0.3 eV
- **Total Signal Accumulation Time:** 1808 s
- **Total Elapsed Time:** 4972 s
- **Number of Scans:** 25
- **Effective Detector Width:** 4.2 eV
Accession #: 01310–04
Host Material: Single crystal SrTiO$_3$
Technique: XPS
Spectral Region: C 1s, Sr 3p

Instrument: Kratos Axis Ultra
Excitation Source: Al K$_\alpha$ monochromatic
Source Energy: 1486.6 eV
Source Strength: 120 W
Source Size: 2 mm × 2 mm
Analyzer Type: spherical sector
Incident Angle: 54°
Emission Angle: 0°
Analyzer Pass Energy: 20 eV
Analyzer Resolution: 0.3 eV
Total Signal Accumulation Time: 4210 s
Total Elapsed Time: 11577.5 s
Number of Scans: 25
Effective Detector Width: 4.2 eV

Accession #: 01310–05
Host Material: Single crystal SrTiO$_3$
Technique: XPS
Spectral Region: Sr 3d

Instrument: Kratos Axis Ultra
Excitation Source: Al K$_\alpha$ monochromatic
Source Energy: 1486.6 eV
Source Strength: 120 W
Source Size: 2 mm × 2 mm
Analyzer Type: spherical sector
Incident Angle: 54°
Emission Angle: 0°
Analyzer Pass Energy: 20 eV
Analyzer Resolution: 0.3 eV
Total Signal Accumulation Time: 1508 s
Total Elapsed Time: 4147 s
Number of Scans: 25
Effective Detector Width: 4.2 eV
**Accession #: 01310–06**
- **Host Material**: Single crystal SrTiO$_3$
- **Technique**: XPS
- **Spectral Region**: Ti $3p$

Instrument: Kratos Axis Ultra
Excitation Source: Al K$_\alpha$ monochromatic
Source Energy: 1486.6 eV
Source Strength: 120 W
Source Size: 2 mm $\times$ 2 mm
Analyzer Type: spherical sector
Incident Angle: 54°
Emission Angle: 0°
Analyzer Pass Energy: 20 eV
Analyzer Resolution: 0.3 eV
Total Signal Accumulation Time: 2010 s
Total Elapsed Time: 5527.5 s
Number of Scans: 25
Effective Detector Width: 4.2 eV

---

**Accession #: 01310–07**
- **Host Material**: Single crystal SrTiO$_3$
- **Technique**: XPS
- **Spectral Region**: Sr $4p$, O 2$s$; valence band

Instrument: Kratos Axis Ultra
Excitation Source: Al K$_\alpha$ monochromatic
Source Energy: 1486.6 eV
Source Strength: 120 W
Source Size: 2 mm $\times$ 2 mm
Analyzer Type: spherical sector
Incident Angle: 54°
Emission Angle: 0°
Analyzer Pass Energy: 20 eV
Analyzer Resolution: 0.3 eV
Total Signal Accumulation Time: 4762 s
Total Elapsed Time: 13995.5 s
Number of Scans: 25
Effective Detector Width: 4.2 eV