

SHARED INSTRUMENTATION FACILITY

Colorado School of Mines' Shared Instrumentation Facility houses a wide range of state of the art instrumentation supporting campus-wide research in Electron Microscopy, Mass Spectrometry, Materials Characterization, Mechanical Testing, Nanofabrication, Scanning Probe and Optical Microscopy, Thin Film Deposition, X-ray Diffraction and Computed Tomography, and X-ray Photoelectron Spectroscopy. Each of these disciplines is staffed by scientists who offer hands-on training, specialized research services, and project consultation. Details regarding selected equipment available at Mines for the proposed work are provided below.

ELECTRON MICROSCOPY INSTRUMENTATION

SPECIMEN PREP CAPABILITIES IN THE ELECTRON MICROSCOPY LAB

GENERAL

- Slow Speed Diamond Saws
- EVACTRON CombiClean Decontaminator

SEM

- JEOL IB-0910CP Cross-Section Polisher
- Hummer IV Sputtering System (Au/C Coater)
- Cressington Carbon Coater

TEM

- 3mm Foil Punch
- South Bay Model 350 3mm TEM Disk Cutter
- Gatan Model 600 Duo Mill Ar ion mill
- Fischione Electropolishing System

FEI HELIOS NANOLAB 600I FIB/SEM

The Helios NanoLab 600i is a SEM/FIB DualBeam workstation with a Ga ion column for imaging and sample milling and Pt deposition (GIS) capability. Nanoscale chemical analysis may be performed with an EDAX energy dispersive X-ray spectroscopy (EDS) system. The instrument is also outfitted with an electron backscattered diffraction (EBSD) system, which allows for crystallographic determination on the nanoscale, and, along with imaging capabilities, 3-D reconstructions of the material composition and crystallography. In situ manipulation for TEM foil extraction is performed using an Omniprobe Autoprobe 200 nano-manipulator, with 10 nm positioning resolution.

- Schottky Field Emission Cathode
- Resolution: 0.9 nm at 15 kV (at eucentric WD); 1.4 nm at 1 kV (at optimum WD)
- Ga Source Focused Ion Beam (FIB) – 0.5 kV to 30 kV
- Platinum Deposition (GIS) System
- Secondary (SEI) and Backscatter (BEI) Imaging
- In-lens SE detector (TLD-SE)
- In-lens BSE detector (TLD-BSE)
- Everhardt-Thornley SE
- Solid-state BF and DF STEM detector
- AutoFIB, AutoTEM, Slice and View, and EBS3 Software

- EDAX “Octane Super” SDD Energy Dispersive Spectroscopy of X-rays (EDS)
- EDAX “Hikari Super” 1400pps Electron Backscatter Diffraction (EBSD) detector
- EDAX TEAM software
- Omniprobe Autoprobe™ 200 Nano-manipulator

FEI QUANTA 600I ENVIRONMENTAL SEM

The Quanta SEM has operating vacuum modes to deal with different types of samples. High Vacuum (HiVac) is the conventional operating mode associated with all scanning electron microscopes. The two other application modes are Low Vacuum (LowVac) and ESEM. In these modes the specimen chamber is at a pressure range of 0.1 to 30 Torr (15 to 4000 Pa). Either mode can use water vapor from a built-in water reservoir, or auxiliary gas supplied by the user. Observation of outgassing or highly charging materials can be made using one of these modes without the need to metal coat the sample.

- Tungsten Cathode
- Secondary (SEI) and Backscatter (BEI) Imaging
- Three modes of operation:
 1. High Vacuum (10^{-6} torr)
 2. Low vacuum (0.1 – 1.0 torr)
 3. ESEM (1.0 – 10 torr)
- EDAX “Element” SDD Energy Dispersive Spectroscopy of X-rays (EDS)
- Large Sample Chamber
- Hot Stages (rated to 1500°C)
- Peltier Cold Stage

FEI TALOS F200X TEM/STEM

The FEI Co. Talos F200X 200keV field emission scanning / transmission electron microscope is located in the CoorsTek Building (Room 001P). The FEI X-FEG high brightness electron source delivers high total current — up to five times the beam current of a standard Schottky FEG — while the integrated EDS system with four silicon drift detectors (SDDs) offers mapping capabilities of up to 10^5 spectra/sec. It has a TEM information limit better than 0.12 nm. The STEM probe allows for an imaging resolution of 0.16 nm. STEM images can be viewed in bright field or with multiple dark field detectors, including a high-angle annular dark field detector (HAADF) allowing for Z-contrast imaging.

- Schottky Field Emission Gun
- Up to 200kV Accelerating Voltage
- Conventional and Scanning Modes (TEM/STEM)
- High Resolution (HREM): 0.12 nm Information Limit
- Super-X EDS for Spectral Imaging
- High Angle Annular (HAADF) and Centered (CDF) Dark Field Modes

FEI TECNAI T12

Tecnai™ G2 Spirit TWIN (T12)

- Accelerating Voltage: 20-120KV
- Gun Type: W Filament/LaB6
- Line resolution (nm): 0.2
- Cs objective (mm): 2.2
- Cc objective (mm): 2.2
- Focal length (mm): 2.8
- Minimum focus step (nm): 3.0

- Maximum eucentric tilt: $\pm 70^\circ$
- Magnification: 18 – 650,000
- Specimen Exchange Time: < 30 seconds
- High tension switching Time: < 1 minute
- X, Y movement: 2 mm
- Elemental Analysis: EDAX Element EDS System
- Image Capture: CD Camera and Film
- Specimen Holders: Single and Double Tilt

JEOL JSF-7000F FIELD EMISSION SEM

The JSM-7000F is a field-emission scanning electron microscope with a Schottky type field-emission gun for the electron source. The instrument is equipped for energy dispersive X-ray spectroscopy (EDS) and electron backscatter diffraction (EBSD) analysis.

- Schottky Field Emission Cathode
- High Resolution (1.2nm @30kV)
- Secondary (SEI) and Backscatter (BEI-TOPO/COMPO) Imaging
- EDAX “Octane Pro” SDD EDS
- EDAX “Hikari Pro” 600pps EBSD detector
- Electron Lithography

PHENOM SEM

The Phenom Scanning Electron Microscope is a tabletop SEM which features combined optical- electron images for easy sample navigation. It is designed for ease of use and rapid sample loading. It can achieve up to 100,000 X magnification with resolution down to 15nm.

TESCAN S8252G RAMAN-SEM/FIB

The TESCAN S8000G is an ultra-high resolution variable pressure Schottky field emission scanning electron microscope/Ga+ focused ion beam instrument for imaging and sample milling and W, Pt, and Co deposition (GIS) capabilities. It is equipped with WITec in situ confocal Raman imaging at 532 nm and 785 nm excitation wavelengths using a 100x objective, NA = 0.75. The SEM/FIB has an Everhart-Thornley detector, two retractable backscatter detectors (one water-cooled), an in-beam multi-detector, in-beam axial detector, and secondary ion detector. The instrument is also capable of 3-D imaging using any of the detectors.

Nanoscale compositional analysis may be performed with an EDAX Octane Elect Plus (30mm²) energy dispersive X-ray spectroscopy (EDS) system with APEX software.

The EDAX Velocity™ Pro EBSD camera offers high-speed electron backscatter diffraction (EBSD) mapping (up to 2500 pps) using a CMOS sensor and can be used in combination with the EDS detector for simultaneous EDS-EBSD data collection.

In situ manipulation for TEM foil extraction is performed using a SmarAct nano-manipulator, with 1 nm positioning resolution and an electron flood gun for charge neutralization during ion beam milling of non-conductive samples.

The Gatan Murano heating stage allows for in situ analysis from room temperature to 950° C.

- SEM Resolution: 0.9 nm at 15 kV (at 1 mm WD)
- Ga Source Focused Ion Beam (FIB) – 0.5 kV to 30 kV, up to 100nA
- Optical resolution: diffraction limited lateral typ. 430 nm @ 532 nm excitation wavelength

- 532 nm, 75 mW diode-pumped solid state laser
- 785 nm, 125 mW diode laser
- Fully motorized, heavy-duty compucentric 5-axis cradle stage (X=256mm, Y=152mm, Z=52mm, Rotation=360°, Bidirectional tilt = -3° to 60°, 8kg weight capacity)

This instrument was acquired through the support of the National Science Foundation (DMR-1828454). The EBSD detector was funded through an ONR-DURIP grant.

MASS SPECTROMETRY INSTRUMENTATION

CAMECA LEAP 4000X SI

The LEAP 4000X Si local electrode atom probe provides 3D nanoscale compositional analysis. Mass spectral data obtained through time-of-flight measurements can be used to identify light mass and heavy mass species (hydrogen out to >1000 Da) with equivalent sensitivity. The mass resolution is sufficient for distinguishing isotopic abundances. The instrument features both laser pulsing and voltage pulsing along with a 90 mm to 160 mm variable flight path.

- Mass resolution (FWHM)* : Voltage Pulse Mode 1:500 ; Laser Pulse Mode 1:1500
 - Mass resolution (FWTM)*: Voltage Pulse Mode 1:180 ; Laser Pulse Mode 1:650
 - Mass resolution (FW1%M)*: Voltage Pulse Mode n/a ; Laser Pulse Mode 1:400
 - Maximum pulse rate (kHz): Voltage Pulse Mode 200 ; Laser Pulse Mode 1,000
 - Base pressure on 50K specimen (Torr) : <1E - 10
 - Minimum specimen temperature (K) : 25
 - Achievable field of view (nm) : 250
 - Lateral resolution (nm): 0.2
 - Depth resolution (nm): 0.05
 - IVAS advanced data analysis software for reconstruction, visualization and analysis of atom probe data sets
 - Plasma cleaner interfaced to load lock provides surface contamination removal
- *For standard Al specimen

IONTOF TOF-SIMS.V

Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) is a highly surface-sensitive analytical technique used to obtain elemental, isotopic, and molecular information from the surface of solid materials and compacted powders. This TOF-SIMS instrument features a Primary Ion Beam operating at 30 keV with a three-lens BiMn cluster nanoprobe. For sputtering sources (Secondary Ion Beams) the TOF.5 can utilize either a Thermal ionization Cesium source, an Oxygen electron impact gas ion source, or a fully integrated gas cluster ion source. The Bi Nanoprobe source provides high analysis currents of up to 20 pA for trace detection spectrometry and high-end depth profiling.

Each point of impact on the sample from the primary ion beam contains the entire mass spectrum as well as the X, Y and Z coordinates of that point of impact. With this information, we can create detailed ion images of the distribution of any species of interest on our sample, both in 2D and in 3D (in depth profile mode).

- High sensitivity with the ability to detect species in the parts-per-million (ppm) to parts-per-billion (ppb) range
- High mass resolution of ~0.00x amu
- Capable of ~80nm spatial resolution
- Can obtain elemental and molecular information from a mass range of 0 to 10,000+ amu simultaneously
- Depth profiling with parallel ion detection
- Species mapping in both 2D and 3D

- Ability to analyze insulators and conductors
- Retrospective analysis

ADDITIONAL FEATURES

- **Argon Gas Cluster Source** provides the ability to detect high mass polymers and depth profile through complex organic materials.
- **In-situ Ga Focused Ion Beam** can analyze extremely rough samples, samples with voids or samples that exhibit strong local variations in density.
- **Extended Dynamic Range Analyzer** extends dynamic range up to seven orders of magnitude, allowing for simultaneous detection of normally saturated matrix species and trace species.
- **Hermetically Sealed Transfer Vessel** ability to analyze atmospheric or moisture-sensitive samples.

SCIEX 5500 TRIPLE QUAD

Liquid Chromatography-Mass Spectrometry is an analytical technique for determining an ion's mass-to-charge ratio by partitioning the particles within a liquid and measuring the time it takes for each particle to travel through a selected mobile phase. Ultimately this helps in determining the contents of a liquid sample and can be used to analyze biochemical, organic and inorganic compounds.

A Triple Quadrupole Mass Spectrometer is a highly sensitive instrument for detecting and quantifying known compounds within a sample. Within the instrument there are three quadrupoles arranged in a series where the first quadrupole acts as a mass filter, the second functions as a collision cell wherein the ions interact with a gas, and the third quadrupole helps to detect the mass range. The ions are then fired towards a detector which analyzes the individual fragments.

SCIEX X500R QTOF

Liquid Chromatography-Mass Spectrometry is an analytical technique for determining an ion's mass-to-charge ratio by partitioning the particles within a liquid and measuring the time it takes for each particle to travel through a selected mobile phase. Ultimately this helps in determining the contents of a liquid sample and can be used to analyze biochemical, organic and inorganic compounds.

A Quadrupole Time-of-Flight Mass Spectrometer is a very sensitive system which can be very beneficial in non-target analysis involving screening a sample for a multitude of unknown compounds. Similar to a Triple Quad MS, there are three quadrupoles arranged in a series. A QToF MS switches out the third quadrupole for a TOF mass analyzer, allowing for greater range of ion detection and mass accuracy. Using a QToF system makes it possible to perform a full ion scan to allow for future analysis of unknown compounds without needing to reacquire data.

THERMO SCIENTIFIC ORBITRAP EXPLORIS 120

Liquid Chromatography-Mass Spectrometry is an analytical technique for determining an ion's mass-to-charge ratio by partitioning the particles within a liquid and measuring the time it takes for each particle to travel through a selected mobile phase. Ultimately this helps in determining the contents of a liquid sample and can be used to analyze biochemical, organic and inorganic compounds.

Orbitrap mass spectrometry is an ion trap mass analyzer that consists of two outer electrodes and a central electrode, which enable it to act as both an analyzer and detector. Ions are "trapped" using electrostatic fields, which causes them to oscillate at frequencies specific to the ion. These frequencies are detected and

measured, and the mass is determined using image current detection. High-resolution mass spectrometers are designed to resolve analytes of interest from interferences.

With Orbitrap high-resolution accurate-mass (HRAM) technology, the Orbitrap mass spectrometer goes further by discriminating ions of interest from interfering ions differing by only very small mass increments; as little as a 1 ppm mass difference. As a result, you substantially reduce the likelihood of false positives and negatives when analyzing complex sample matrices. Orbitrap also allows for detection of dilute compounds, quantifying to less than 1 ppb concentrations. These systems allow for targeted (scanning for known contaminants) as well as non-targeted analysis and suspect screening (unknown contaminants)

MATERIALS CHARACTERIZATION INSTRUMENTATION

4-POINT ELECTRICAL PROBE

Probe station with 4 micropositioner probes under an optical microscope, connected to a two-channel Keithley SUM and programmable LCR meter. This system is also capable of performing 4 point probe resistivity measurements.

FTIR SPECTROMETER/ELLIPSOMETER

Nicolet 6700 research-grade Fourier Transform Infrared (FTIR) Spectrometer

- Standard spectral range: 350/cm to 7800/cm (28.5 microns to 1.28 microns = 1280 nm)
- Spectral resolution as low as 1/cm
- ETC Everglo source
- High resolution dynamically aligned interferometer
- KBr beamsplitter
- Gold-coated optics for high throughput
- Thermoelectrically cooled DLaTGS detector with KBr window
- Liquid nitrogen cooled MCT-A detector with KRS-5 window
- Purged with air filtered to reduce water vapor and carbon dioxide
- Operating and spectral analysis software: OMNIC by Thermo Fisher

Default sampling mode: transmission/absorbance

Sample holder with automatic reference acquisition

Available sampling mode: Attenuated total reflectance (ATR)

- Sentech Model SE 910-50 infrared ellipsometer attachment
- Optical path: polarizer-sample-compensator-analyzer
- Variable incident angle between 40 and 90 degrees
- Manual sample tilt and height adjustment
- Illuminated spot size: 2 mm x 5 mm at 70 degree incident angle

HALL SYSTEM

The HL5500PC is a high-performance Hall Effect Measurement System. It enables measurement of resistivity, carrier concentration and mobility on a wide range of semiconductors and with minimum effort in sample preparation. The HL5500PC is designed as a modular system and the basic instrument can measure sheet resistivity's up to a few MOhm/square and Hall voltages of a few μV . Samples can have Van der Pauw, bar or

bridge shaped geometries, and dual temperature measurements (at room temperature and 77 K) are readily achievable.

- Thickness should be less than 1/15 of the peripheral length (less than 1mm), and uniform to $\pm 1\%$.
- Sheet resistivity's of 0.1 m Ω /square to in excess of 1 M Ω /square
- Optional to extend sheet resistivity measurements to 1011 Ω /square
- Max Measurement Diameter: 25 mm
- Magnet: Permanent with field reversal by magnet rotation
- Support for van der Pauw, Hall bar and bridge samples
- Integration, delay & repeat measurement modes increase flexibility and accuracy on difficult to measure samples
- Easy to export data and information

JANIS CRYSTAT

Janis SHI-4-2 cryostat for electrical transport measurements. The Janis Cryostat can maintain a temperature down to 4 kelvin and has 24 leads for electrical transport measurements. It is connected to a function generation, a digital multimeter, and a lock in amplifier.

SOLAR SIMULATOR

A PV Measurements inc. 1000W class A solar simulator with 16 cm x 16 cm uniform area calibrated to an AM1.5 spectrum. It has an automated measurement program to perform current voltage sweeps. The system is also equipped with external quantum efficiency measurement setup.

UV-VIS SPECTROMETER

The CARY 5G is a high-performance UV-VIS and NIR spectrophotometer, with a 175-3300 nm range. Ideal for measuring the absorption profiles of thin film materials.

WOOLLAM M-2000 ELLIPSOMETER

Model X-210

- Simultaneous measurement at 485 wavelengths between 210 nm and 1000 nm
- Rotating compensator optical path
- Data acquisition for a complete spectrum in as little as 1 sec
- Horizontal sample stage with vacuum chuck sample hold
- Variable incident angle between 45 and 90 degrees
- Automated sample height adjustment
- Beam diameter 2-5 mm
- Focusing optics can be installed to reduce illuminated spot to 0.3 x 0.9 mm
- CompleteEASE software for data acquisition and analysis

MECHANICAL TESTING INSTRUMENTATION

The Mechanical Testing (MT) labs within the Mines Shared Instrumentation Facility (SIF) include a variety of monotonic, fatigue, temperature, and strain measurement capabilities. These capabilities cover a wide range of load capacities and resolutions, displacement rates, loading configurations, and custom fixturing. Strain measurement capabilities are available for 1D, 2D, and 3D using extensometers and digital image correlation (DIC) across temperature ranges of -129 to 1200 °C.

DSI GLEEBLE 3500-GTC

The DSI Gleeble 3500-GTC is a highly specialized system for research in welding and high temperature mechanical properties such as hot formability in metals. The system can be configured for tension/compression or torsion with load capacities of 45 kN and 50 Nm, displacement rates up to 1,000 mm/s and 25 rev/s, resistive heating rates up to 10,000 °C/s to 1750 °C, and surface cooling rates up to 10,000 °C through water or gas quenching.

MTS EXCEED E22 IMPACT TESTER

The MTS Exceed E22 is a Charpy impact tester with 450 J energy capacity, automatic specimen feeding and pendulum return, and a 30-specimen cooling chamber for temperatures down to 180 °C.

MT - ELECTROMECHANICAL LOAD FRAMES

- **MARK-10 ESM1500**

The MARK-10 ESM1500 is a 6.7 kN uniaxial electromechanical load frame with fixtures for tension/compression, bending, clevis, wire pull, and hook, and resolution down to 0.02 N for 50 N capacity. Optomechanics, cameras, and lighting can be configured on an optics table for digital image correlation strain measurement.

- **MTS ALLIANCE RT/100**

The MTS Alliance RT/100 is a 100 kN uniaxial electromechanical load frame that can be configured with a wide range of fixturing for quasistatic testing, including sheet and bar bending, and drawing.

- **INSTRU-MET RENEW 1125**

The Instru-Met ReNew 1125 is a 100 kN uniaxial or 225 Nm fixed/free torsion electromechanical load frame that can be configured with a wide range of fixturing for quasistatic testing. This fixturing includes an environmental chamber for hydrogen embrittlement and a box furnace for testing up to 1200 °C.

MT- FATIGUE MACHINES

- **SATEC SONNTAG FATIGUE TESTING SYSTEM SF-1-U**

The SATEC Sonntag SF-1-U is a shaker-table style fatigue system configurable for bending, Krouse-type, and torsion up to 30 Hz. Load capacities are up to 680 Nm bending and 2700 Nm torsion.

- **FATIGUE DYNAMICS RBF-200 ROTATING BENDING FATIGUE**

The DIC Fatigue Dynamics RBF-200 is rotating bending fatigue machine that can operate up to 83 Hz with a load capacity up to 23 Nm.

MT - SERVOHYDRAULIC LOAD FRAMES

- **MTS LANDMARK 370.10**

The MTS Landmark 370.10 is a 100 kN uniaxial servohydraulic load frame equipped with an alignment fixture, hydraulic wedge grips, and various wedges for rectangular and circular specimen geometries, making it well suited for fatigue testing. It can be used in conjunction with an induction furnace for heating to 1300 °C.

- **MTS LANDMARK 370.25**

The MTS Landmark 370.25 is a 250 kN uniaxial servohydraulic load frame equipped with an alignment fixture, hydraulic wedge grips, and various wedges for rectangular and circular specimen geometries. It can be used in conjunction with an MTS environmental chamber for low and high temperature testing from -129 to 315 °C.

- **MTS 312.21 TOP ACTUATOR**

The MTS 312.21 is a 100 kN uniaxial servohydraulic load frame equipped with a top mounted actuator and a pattern threaded baseplate. This configuration provides a stable mounting surface for large custom fixturing, such as environmental chambers.

- **MTS 312.21 HYDRAULIC GRIPS**

The MTS 312.21 is a 100 kN uniaxial servohydraulic load frame equipped with an alignment fixture, hydraulic wedge grips, and various wedges for rectangular and circular specimen geometries, making it well suited for fatigue testing.

- **MTS 312.21 BENDING UNDER TENSION**

The MTS 312.21 is a 50 kN uniaxial servohydraulic load frame that can be configured with a truss-mounted orthogonal actuator for sheet metal formability studies. Fixed and free mandrels of various sizes and materials are available.

- **MTS 312.41**

The MTS 312.41 is a 450 kN uniaxial servohydraulic load frame that can be configured with a separate hydraulic clamp for sheet metal formability studies such as stamping and hole expansion.

- **MTS 810 MATERIAL TEST SYSTEM 318.50**

The MTS 810 Material Test System 318.50 is a 50 kN high-rate uniaxial servohydraulic load frame capable of displacement rates up to 10 m/s.

NANOFABRICATION INSTRUMENTATION

Mines' Shared Instrumentation Facility houses two Class 1,000 Cleanrooms with photolithography capabilities for substrates up to 3 inch (76 mm) diameter and features down to 2 µm resolution and house the equipment outlined below.

ABM UV MASK ALIGNER

The ABM mask aligner features an intensity-controlled 6"x6" illumination area, strong illumination at both 400 and 350, two simultaneous operating alignment cameras, auto-leveling sample mount, micrometer adjustments, and semiautomatic operation. It is currently set up for use with 4" masks and <1" samples but adjustments can be made upon request.

AUTOGLOW 200 REACTIVE ION ETCHER

The AutoGlow 200 reactive ion etcher is a table-top plasma system that can be used for plasma cleaning or RIE processing with O₂ and SF₆ plasmas. It can process as low as 10 W, or as high as 300 W in one-watt increments. The AutoGlow 200 is suitable for lab, failure analysis, or production applications. It can perform a host of applications, including cleaning, removing photoresist, prebonding, organic removal, activation and plasma etching.

DIFFUSION FURNACES

Tube furnace used in the manufacturing of semiconductor components. Used to add doping impurities into high purity silicon wafers, thereby creating embedded semiconductor devices.

DRY OXIDATION FURNACE

Furnace used for growing dry oxides.

HIGH TEMPERATURE FURNACE

6"x6"x6" muffle furnace, capable of holding sustained temperatures of up to 1400 C.

RAPID THERMAL ANNEALER

The ULVAC-RIKO MILA-5000 mini lamp annealer provides rapid heating of a wafer from ambient temperature to approximately desired temperature in controlled gas environments. As soon as the wafer reaches this temperature, it is held there for a few seconds and then cooled. Temperature range: room temperature to about 1200 °C. Sample size: 20 x t2 (mm).

VACUUM FURNACE

A vacuum furnace is a type of furnace in which the product in the furnace is surrounded by a vacuum during processing. The absence of air or other gases prevents oxidation and heat loss from the product through convection, and removes a source of contamination.

WET OXIDATION FURNACE

Wet oxidation uses clean steam. The H₂O molecule is smaller than the O₂ molecule and diffuses through the silicon dioxide layer faster. This allows for the growth of thicker films.

KARL SUSS MASK ALIGNER

Karl Suss MJB3 UV400 Mask Aligner is an instrument enabling photolithography, which is a microfabrication process used to selectively remove parts of a thin film to create a pattern or a design onto a substrate by means of UV lamp. It fits substrates up to 6" x 6" and exposes with a UV400nm source at 250W.

PLASMA CLEANER

The March CS 1701 Reactive Ion Etcher delivers performance often associated with high-investment etching tools. The system is excellent for metal etching, silicide etching, and etching of III-V compounds, anisotropic etching of nitrides, oxides and polyimides.

Key performance features of the CS 1701 system include the large DC bias and the ability to control process pressure independent of gas flow. The system allows users a wide variety of etch profiles ranging from anisotropic requiring high aspect ratios to sloped walls. The system has 3 process gases (O₂, Ar, SF₆) and a N₂ purge.

PLASMA PREEN

The Plasma-Preen System is a plasma cleaning/etching system with O₂ and Ar capabilities which uses microwaves to excite the plasma.

SPIN COATER/HOT PLATE

Spin coating is a procedure used to deposit solution processed materials into uniform thin films onto flat substrates. Film thickness can be controlled by varying spin speed from 100 – 10,000 RPM.

WIRE BONDER

The TPT hb05 is a benchtop manual wire bonding system with gold, silver, aluminum or copper wire and a 6:1 mouse ratio. Ideal for attaching gold contact wires to microscopic features for electrical measurement.

SCANNING PROBE AND OPTICAL MICROSCOPY INSTRUMENTATION

ASYLUM MFP-3D SCANNING PROBE MICROSCOPE

The Asylum MFP-3D atomic force microscope is coupled to an optical microscope (Olympus) for simultaneous imaging and physical properties measurements at the nanoscale for a wide range of advanced materials in renewable energy and life sciences. We can measure electrical and mechanical properties of materials in direct registry with topography at nanoscale resolution under their designed operating conditions (e.g illumination of photovoltaics and hydrated conditions for biological). The measurement of interfacial physical properties at small length scales is essential to the development of the next generation of materials for renewable energy and life sciences. Specific advanced capabilities beyond standard SPM modes (contact, tapping, phase) include:

- **Optical Microscopy:** The AFM head is integrated with an inverted optical microscope, facilitating the quick identification of the specific region of interest and enables optical stimulation to obtain properties such as a photoconductivity or fluorescence in registry with topology.
- **Electro/Mechanical Measurements:** The instrument enables spatially resolved measurements of critical material properties such as conductivity, piezoelectricity, Kelvin Probe, modulus, and viscoelasticity.
- **Environmental Control:** Samples may be evaluated under controlled conditions: temperature (−35°C to 300°C), humidity, fluid cells, and illumination intensity/wavelength.

We gratefully acknowledge the National Science Foundation and Colorado School of Mines for funding this facility through award [#CBET-1532179](#).

DIGITAL INSTRUMENTS AFM

The Digital Instruments Atomic Force Microscope is a high-resolution scanning probe microscope with sub-nanometer vertical resolution and sub-micron horizontal resolution. The system uses a sharp tip on the edge of a cantilever to scan a samples surface and record fluctuations. It can be used to characterize surface roughness, grain boundaries, lithographic structures, and polymeric materials.

KEYENCE VHX-5000

The Keyence VHX-5000 is a digital optical microscope with up to 5000X zoom, 2D and 3D image stitching capabilities, and measurement analysis software.

PROFILOMETER

The D-600 stylus profilometer is an instrument used to measure a surface's profile to quantify its roughness and step heights. The D-600 profilometer can measure fluctuations in surface profile from 1200um down to the nanometer scale.

WITEC LASER CONFOCAL RAMAN MICROSCOPE

This instrument is a WITec Alpha300 is a 532 nm laser confocal microscope equipped with a Raman spectrometer for point, line, area, and volume Raman scans.

THIN FILM DEPOSITION INSTRUMENTATION

AJA SPUTTERING SYSTEM

The AJA is a 4-gun magnetron sputtering system with a sputter-up configuration. The system has the capability to perform RF sputtering deposition for the deposition of ceramic materials, is configured to deposit magnetic materials, and can sputter multiple materials simultaneously.

AJA MULTI-TECHNIQUE DEPOSITION SYSTEM

Ultra High Vacuum thin film deposition system with a 6 pocket e-beam source, 5 magnetron sputtering sources, and an ion gun source. The e-beam system uses 15cc crucibles with motorized indexing and a 5 kW high voltage power supply with integral sweep control. The sputtering system uses 2" wafers, including one with a retractable bellows allowing for a < 3" substrate to target working distance. It has 2 750 W DC generators and 3 300 W RF generators to allow for simultaneous deposition from multiple sources. The system also features integral gas injector to allow for reactive sputtering. System fits up to 4" diameter substrates and can perform sample heating up to 800 C, and contains an isolated oxidation chamber.

ANGSTROM THERMAL EVAPORATOR

The Angstrom thermal evaporator is a thermal evaporation system dedicated to the evaporation of metals (gold, silver, aluminum, and copper.) It has an automated deposition rate controller for ease of use and the creation of consistent reproducible films.

HIGH TEMPERATURE THERMAL EVAPORATOR

In thermal evaporation, a source material is evaporated in a vacuum through the application of a large applied current. The vacuum allows vapor particles to travel directly to the substrate, where they condense back to a solid state. The Large thermal evaporator has 4 material holders which can be used for a variety of evaporable materials, and a large substrate mount that can hold 16 3"x3" substrates.

SEMICORE SPUTTERING SYSTEM

The Semicore is a 3-gun magnetron DC sputtering system with a sputter-down configuration for the deposition of high melting point metals. The system has the capability to do subsequent layered deposition of multiple metals.

TABLETOP GOLD SPUTTER COATER

The Denton nanocoater is a rapid deposition sputtering system configured to deposit a 20nm gold coating on samples in order to prevent surface oxidation or to provide surface conductivity for e-beam measurements.

X-RAY DIFFRACTION & COMPUTED TOMOGRAPHY INSTRUMENTATION

PANALYTICAL EMPYREAN X-RAY DIFFRACTOMETER

The Panalytical Empyrean X-ray diffractometer provides crystallographic and compositional information critical to understanding part mechanical performance. It features small- and wide-angle X-ray scattering (SAXS/WAXS) and has the ability to test samples at temperatures ranging from -200 °C to 1100 °C. It can also capture information on texture, residual stress and pair distribution functions.

- Cu and Mo radiation for low- and high-energy X-ray diffraction (XRD)
- Reflection/transmission geometry with rotating sample for improved statistics
- Spinning capillary

- Bragg–Brentano optics and focusing geometry
- Residual strain measurements
- Cu/Mo focusing mirror and monocrapillary 100 μm beam for microdiffraction
- 5-axis Eulerian cradle for texture mapping
- SAXS/WAXS
- Grazing incidence XRD
- Pair distribution function
- Galipix 3D area detector
- In situ stages from -190 up to 1100 $^{\circ}\text{C}$ (-328 to 2012 $^{\circ}\text{F}$) with 3-axis cradle
- Cr, Cu and Mo X-ray tubes available for variety of measurements
- Cr base high resolution residual stress including parallel beam optic and microbeam dual mask set

PANALYTICAL X'PERT PRO X-RAY DIFFRACTOMETER

This PANalytical (nee Philips) instrument is equipped with a versatile computer-controlled diffractometer and is ideal for routine XRD analysis of powder/polycrystalline specimens. Collection and search software includes the current ICDD database.

- Routine powder/polycrystalline diffraction
- Computer Controlled Stage with X'pert Pro MPD
- Data Collector and DataView Software
- HighScore Search Software
- Current ICDD Database

ZEISS VERSA X-RAY MICROSCOPE

The Zeiss Xradia Versa 3D X-ray microscope enables cutting-edge, nondestructive tomographic imaging and grain reconstruction. X-ray tomography ($\mu\text{-XCT}$) allows for the collection of both surface and internal renderings, which are used to distinguish between phases and identify defects such as porosity. Nondestructive diffraction contrast tomography (DCT) provides direct 3D crystallographic grain reconstructions for crystalline materials. Our lab offers the unique ability to first nondestructively characterize pore distributions in sample parts using the Zeiss Xradia Versa, then to mechanically test those same parts using the load frames described below to correlate defect structures and mechanical behavior.

- Absorption contrast tomography: resolution to 0.7 μm ; up to 160 kV to probe metallic samples up to 4 mm in diameter; automated center shift and reconstruction; automated ring artifact elimination
- Phase contrast tomography: improved resolution at phase boundaries to distinguish particle dispersions
- Dual-energy tomography: low- and high-energy scans allow for segmentation based on differential X-ray absorption
- Diffraction contrast tomography: grain mapping provides crystallographic orientation of samples; grain size approximation enables the preparation of samples for synchrotron experiments
- In situ load frame for testing samples under tensile or compression up to 5 kN

X-RAY PHOTOELECTRON SPECTROSCOPY

ROCKY MOUNTAIN ENVIRONMENTAL XPS USER FACILITY

The Rocky Mountain Environmental X-ray Photoelectron Spectroscopy (E-XPS) center is a user facility for state-of-the-art surface analysis measurements.

XPS measures material surface compositions by measuring the intensity of photoelectrons emitted as a function of the incident X-ray energy. Spectra features are used to identify the surface species present and calculate the fraction of the surface occupied by each.

The Rocky Mountain E-XPS extends these traditional capabilities by enabling measurements in a range of environmental conditions.

The instrument, based on the HiPP lab system from Scienta Omicron, can measure XPS at various pressures and temperatures, and with variable chemical compositions.

Unlike traditional UHV XPS systems, the Rocky Mountain E-XPS can therefore look at surface states for functional materials in relevant environments and with optional electronic biasing for analysis of *non-equilibrated* surface states.

SOURCE

The HiPP Lab from Scienta Omicron utilizes a high power, high energy resolution monochromated Al-K α source with 600 W continuous operation and modified for near-ambient pressure XPS measurements.'

ANALYZER

The energy analyzer boasts the following specifications:

- Energy resolution < 15 meV FWHM at 20 eV pass energy and 500 eV kinetic energy
- Pass energies of 20, 50, 100, 200, and 500 eV.
- The analyzer can operate in standard transmission mode, or collect one-shot measurements to analyze spectra as a function of X-ray energy and either angle (angular mode) or lateral position (spatial mode).
- Transmission mode kinetic energy range: 20 eV – 1500 eV
- Angular mode kinetic energy range: 100 eV – 1500 eV. Parallel angular range: ± 9 degrees.
- Spatial mode kinetic energy range: 20 eV – 1500 eV. Spatial resolution: < 10 μm

SAMPLE ENVIRONMENT CONDITIONS

- Gas pressures of up to 30 mbar
- Temperatures of up to 700 C.
- Gas flow management system allows mixing of two separate feed gases, controlled via mass flow controllers, plus optional water vapor.
- Chamber exhaust composition quantified and monitored via quadrupole mass spectrometer.
- Optional electrical leads for *operando* biasing of samples

SOFTWARE

- Custom Python-based software package for analysis of in situ time resolved XPS analysis
- CASA XPS for standard XPS data processing