A Guide to Electrical Characterization of Materials

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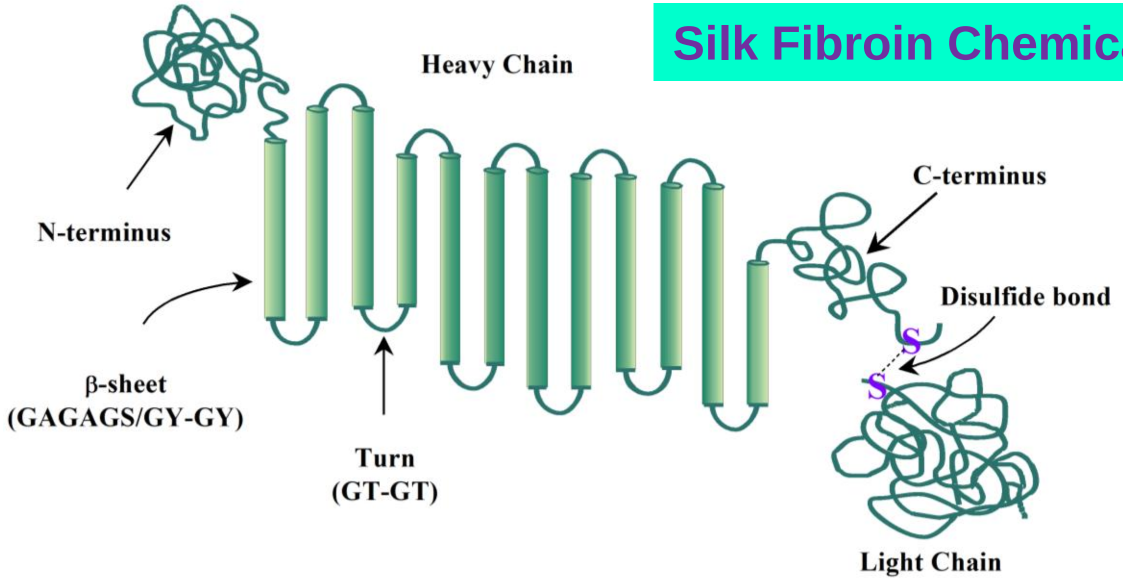
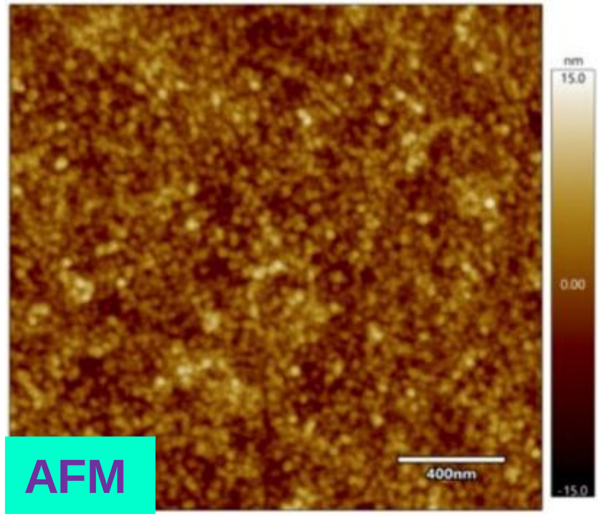
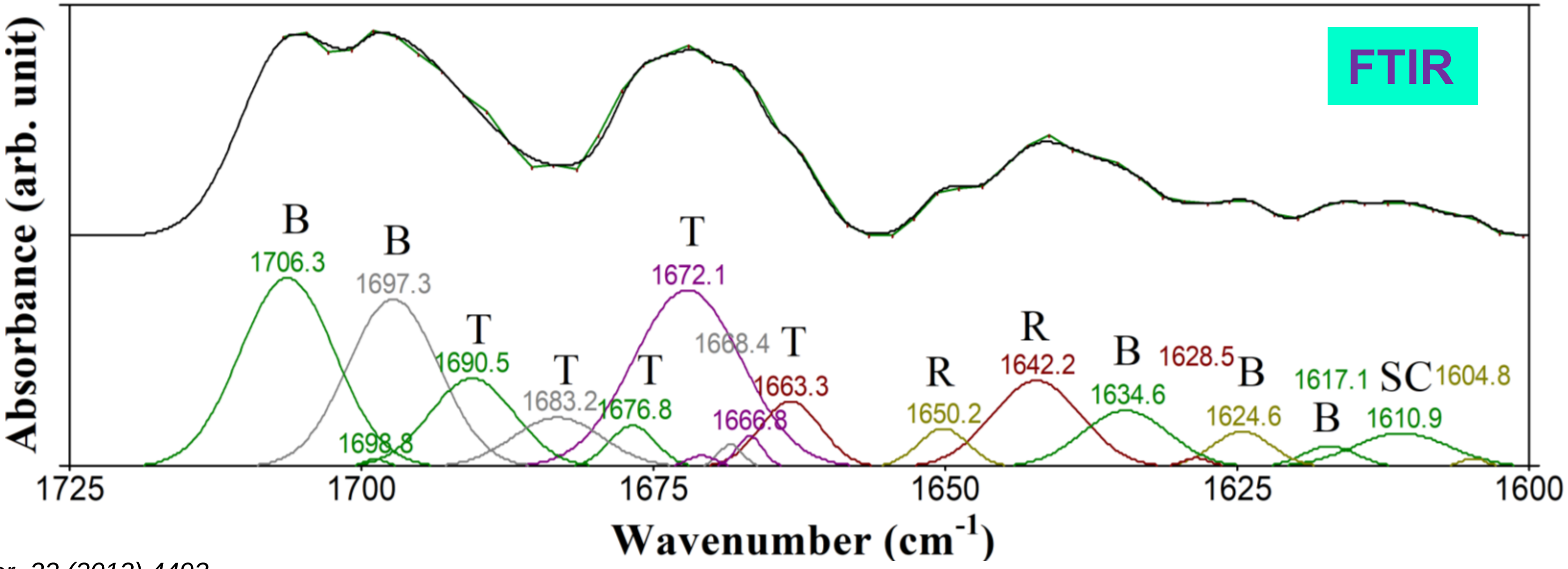
Silk Cocoon



Silk Fibroin Chemical Structure



AFM



FTIR

Adv. Funct. Mater. 22 (2012) 4493

Purpose of Electrical Characterization?

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Evaluate Material Suitability

- Is the material conductive, semiconductive, or insulating?
- Does it meet electrical property specs for the application?

Ensure Process & Quality Control

- Monitor resistance, defects, non-uniformity
- Used in fab lines for QC and yield improvement

Understand Charge Transport

- Identify mechanisms: Ohmic, tunneling, hopping, etc.
- Essential for organic, neuromorphic, or 2D materials

Optimize Device Performance

- Tune fabrication: mobility, on/off ratio, threshold voltage
- Minimize parasitics and leakage

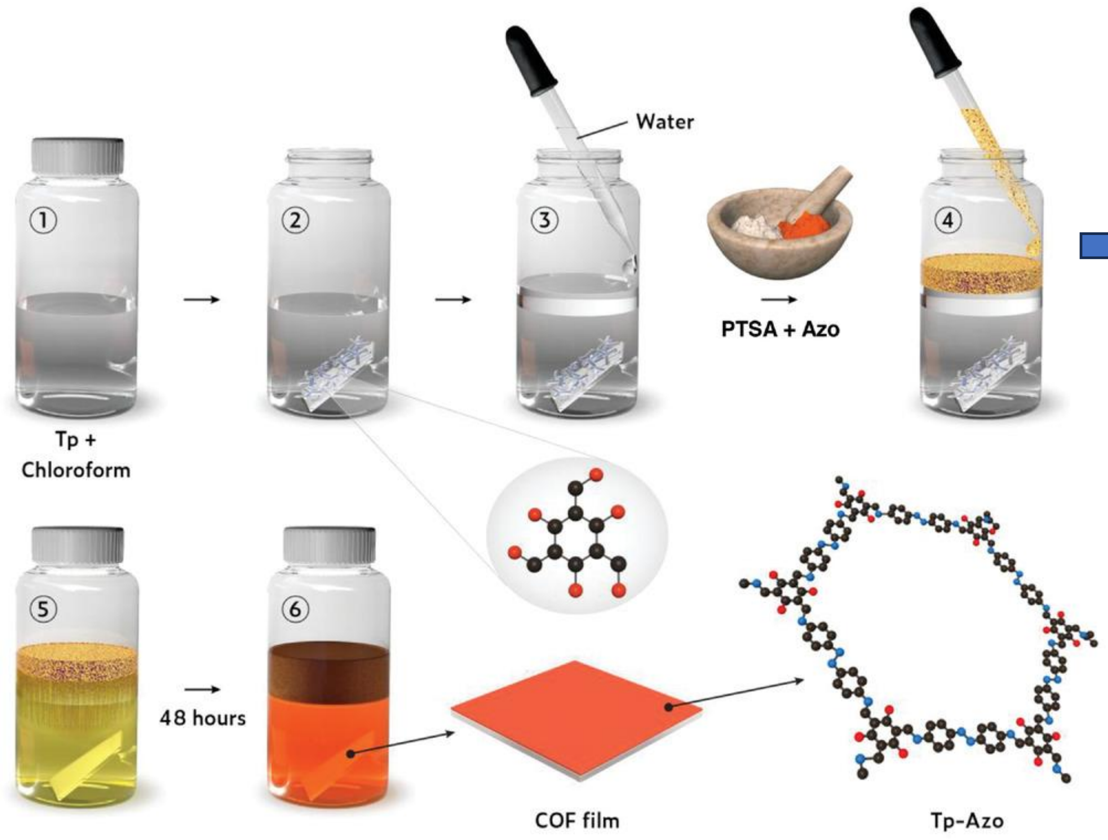
What is Electrical Characterization?

What is Electrical Characterization?

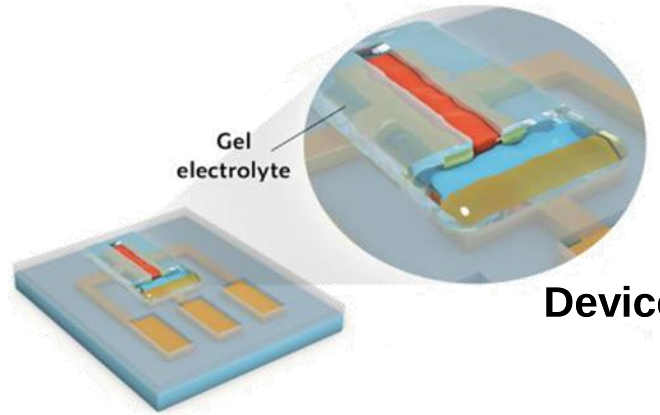
Electrical Characterization?

1. Device Fabrication
2. Device Architecture
3. Metal Contact Type?
4. Interfacial Layer
5. Contamination
6. Proper Litho Tool
7. Measurement Environment
8. Proper Probing
9. Proper Measurement Tool
10. Device-specific Measurement Protocol
11. Device Reliability
12. Consumer-level Device

Material → Fabrication → Measurement → Device Performance

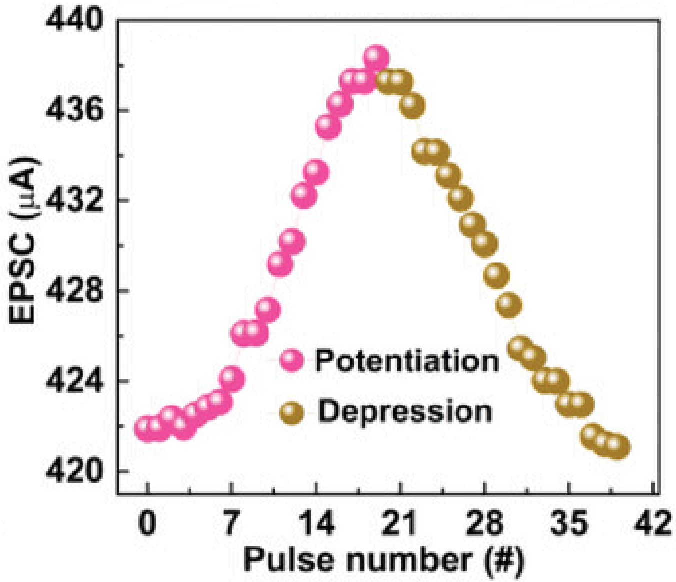


Thin Film Preparation



Device Fabrication

Measurement



Characterization

Adv. Funct. Mat., 32 (2022) 2201120

Probing Methods…

Probing Methods…

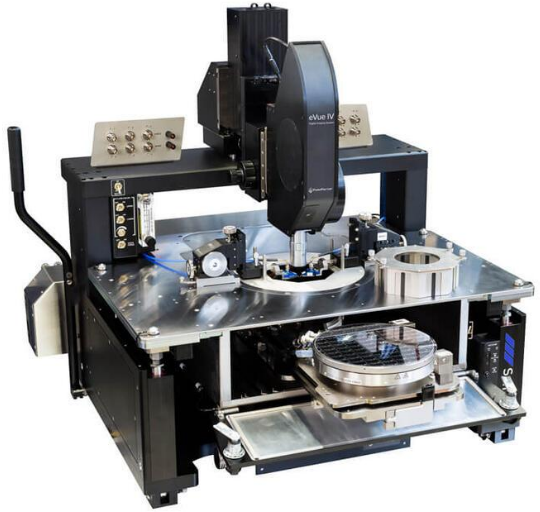
4-Point Probe Configuration:
- Separate current and voltage leads
- Eliminates contact resistance from measurement
- ☑ Accurate for resistivity/conductivity

2-Point Probe Configuration:
- Current and voltage through same contacts
- Simpler setup but includes contact + lead resistance
- ☑ Good for qualitative data

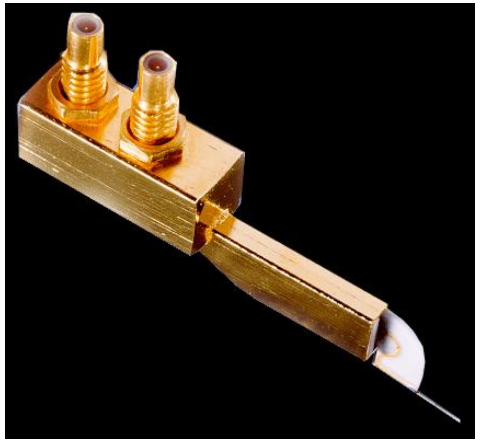
- 4-point probe tool
- Hall effect tool
- PPMS

- DMM
- SMU

Keysight B1500A

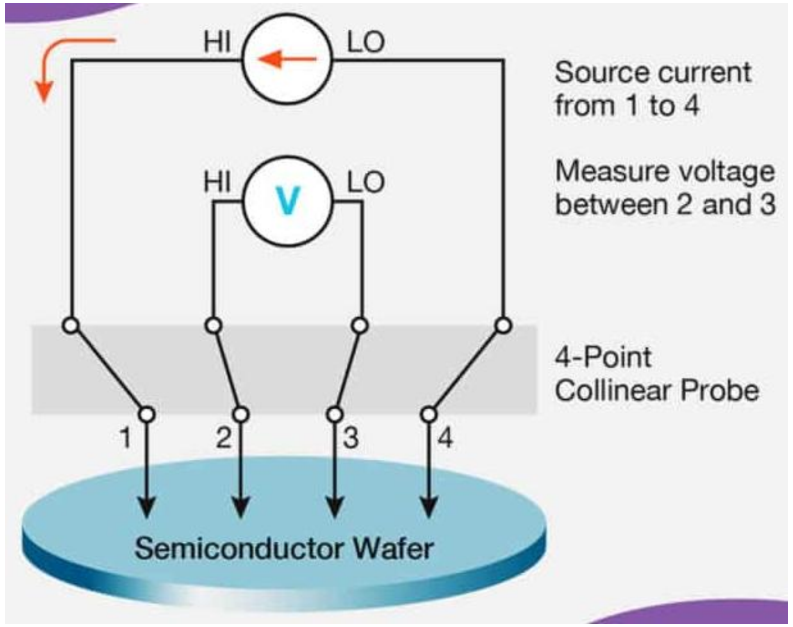


Cascade Summit Probe Station



Current ~ fA-level

Collinear 4-Point Probe



Collinear Four Point Probe measurement

$$R_S = \frac{\pi}{\ln(2)} . \frac{V}{I} \approx 4.532 . \frac{V}{I}$$

If the thickness of thin films << probe spacing

Advantages:

•Contact resistance eliminated from measurement.

•Accurate for both conductive and semiconductive materials.

•Simple and non-destructive (for many materials).

•Applicable to thin films, bulk semiconductors, and even graphene, MXenes, *etc.*

Condition:

- Equally spaced probes
- Homogeneous and flat surface thin films
- Ohmic contacts
- Constant temperature

! Limitations:

•Requires flat, clean surface.

•Inaccurate if probe spacing is comparable to sample dimensions.

•Not ideal for very high-resistance materials.

•Needs correction for non-infinite sample size or layered materials.

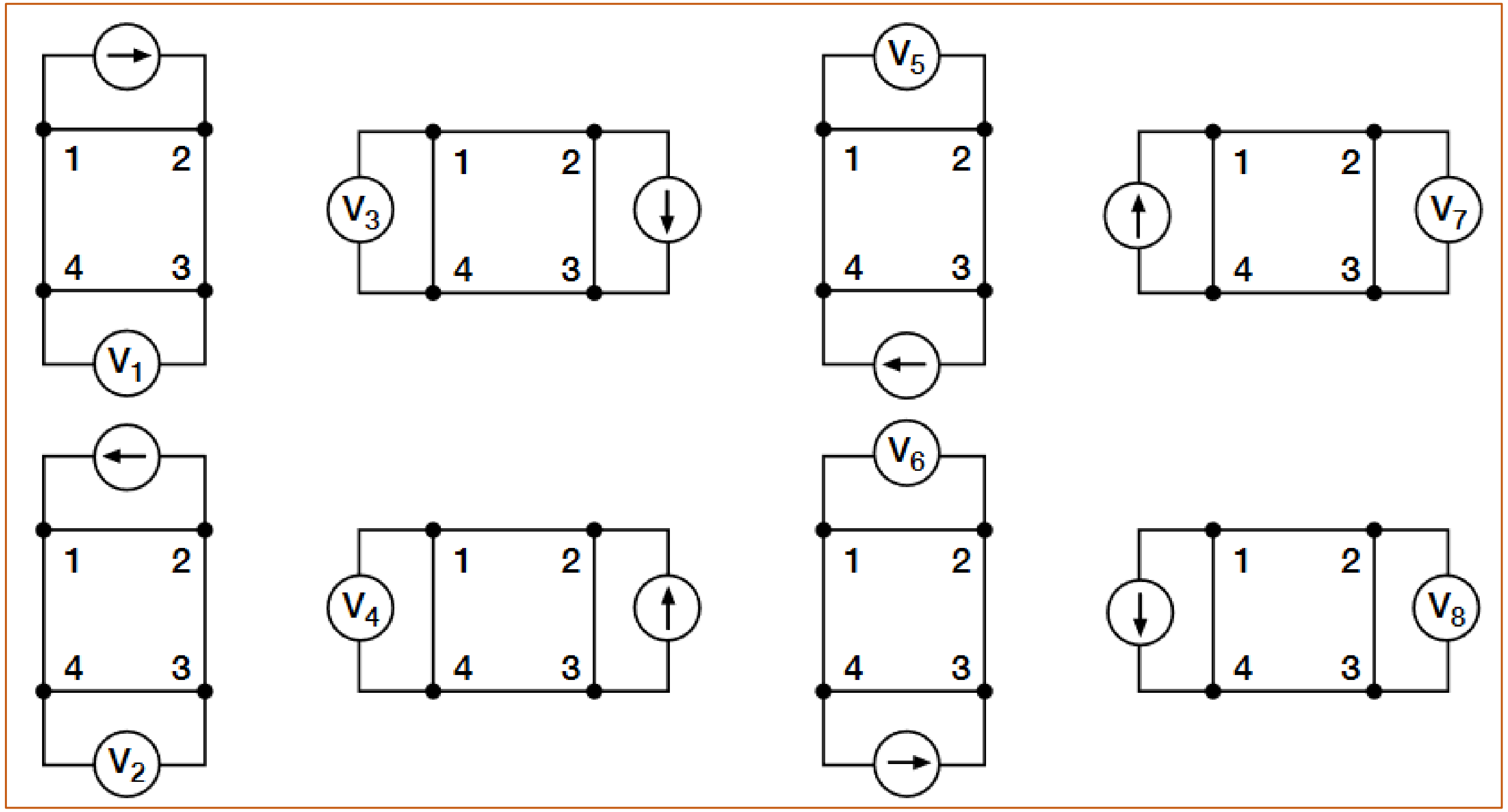
4-Probe Tool

Advanced Instrument Technology 4 probe
Model Number: CMT-SR2000N

Target Parameters

- Resistivity
- Sheet Resistance

Van Der Pauw Technique



$$R_S = \frac{\pi}{\ln(2)} \cdot \frac{V}{I} \approx 4.532.\frac{(R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7 + R_8)}{8}$$

Key Advantages:

•Works on arbitrary-shaped samples (not limited to squares or rectangles).

•High accuracy, especially for thin films and small samples.

Disadvantage:

•Requires accurate edge contacts and full device fabrication steps

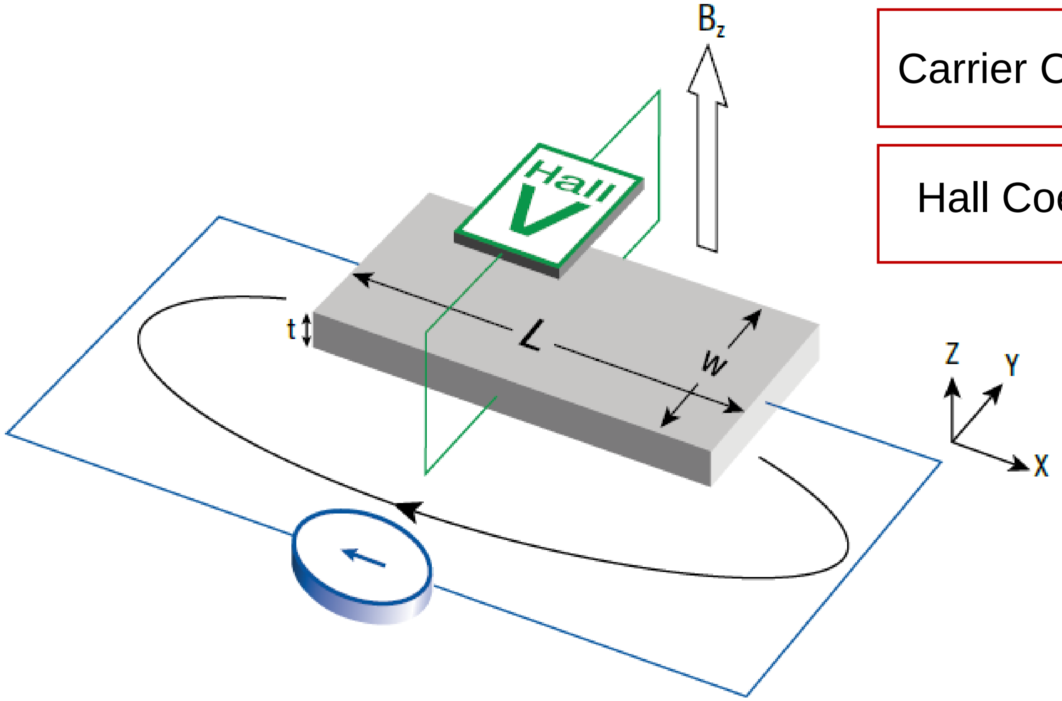
• Contacts must be small and ohmic.

Target Parameters

•Resistivity
•Sheet Resistance

Tools: Keithley 2400, 2450

Hall Effect

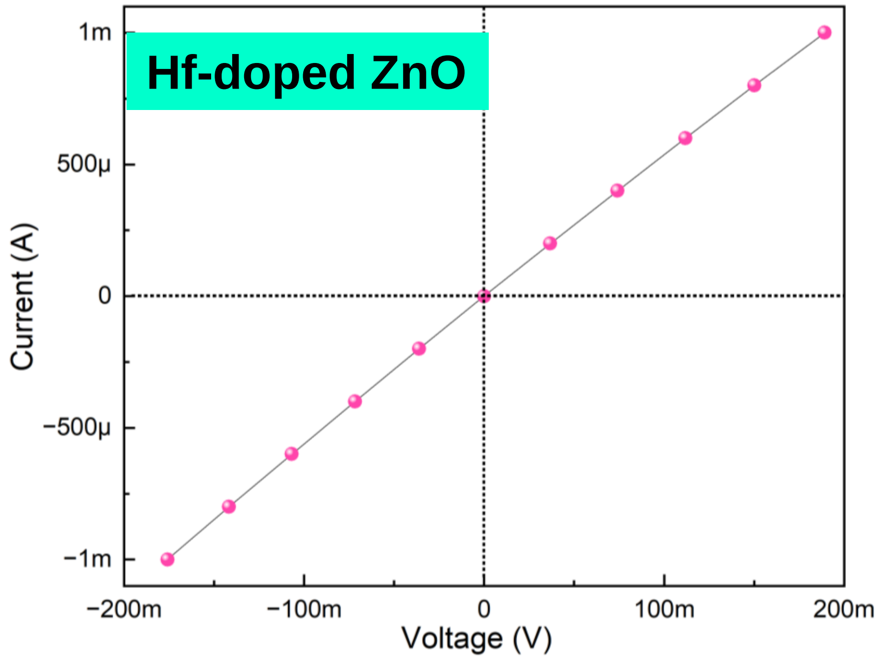


Hall voltage measurement configurations

Carrier Concentration, n: $\frac{I \cdot B}{|q| \cdot V_H \cdot d}$

Hall Coefficient R_H: $\frac{V_H \cdot d}{I \cdot B}$

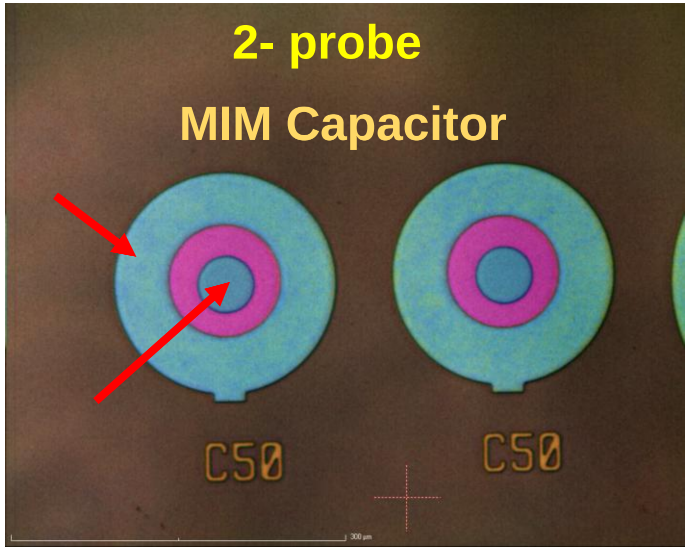
Mobility μ: $\frac{|R_H|}{R_s \cdot d}$

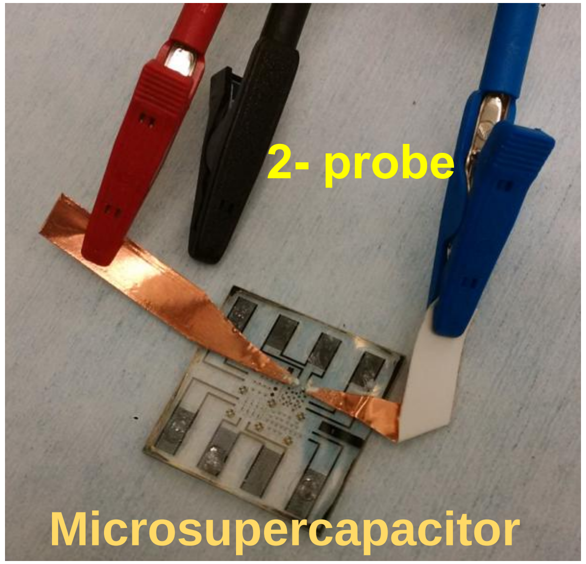


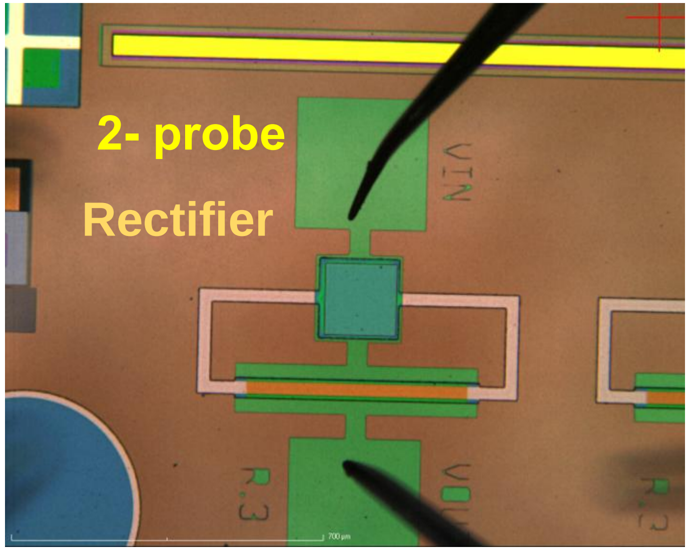
Caution!: Exfoliated 2D films, Spray-coated thin films, Spin-coated thin films.

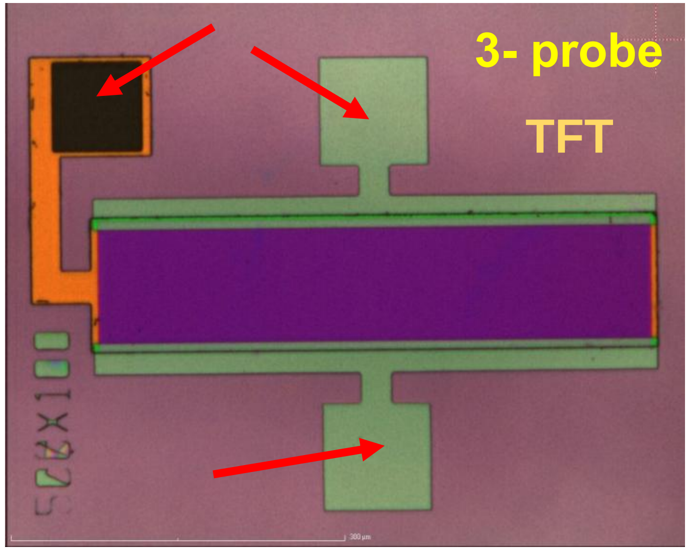
Caution!: Samples should be thin, flat, and homogeneous in thickness, with four ohmic contacts at the four corners.

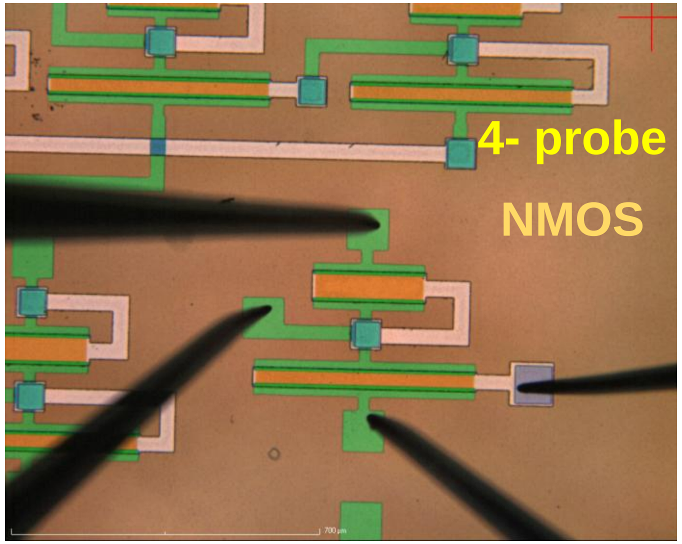
Probing Methods Example

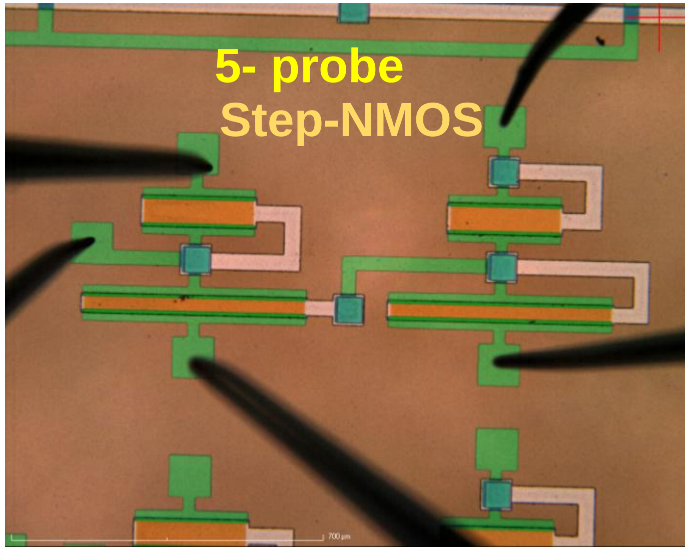












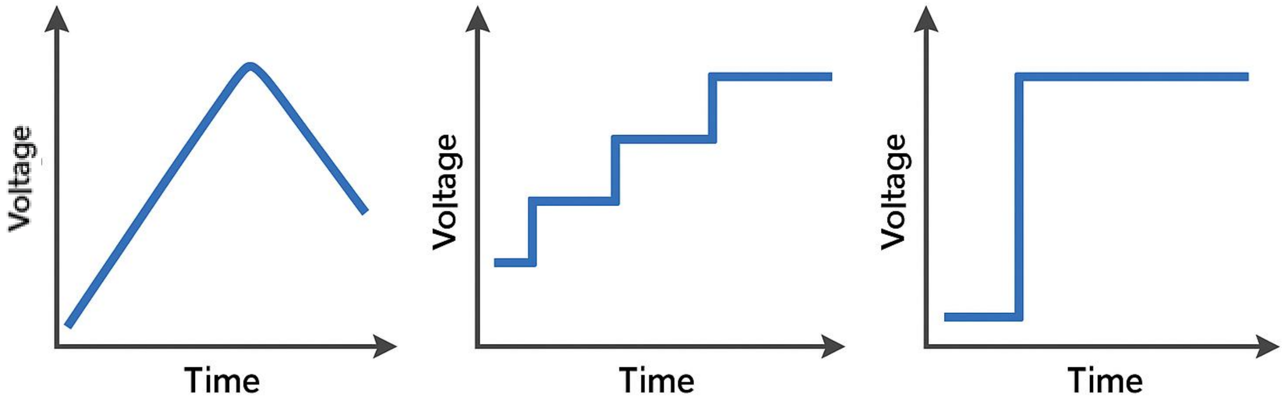
Biasing…

DC Measurements – Basics

•Why Use DC?
- •Simple and fundamental
- •Reveals linear and nonlinear conduction behaviors
- •Widely used for electronics devices characteristics

•Basic Parameters Measured:
- •Resistance / Conductance
- •Current–Voltage (I–V) behavior
- •Threshold voltage (in FETs)
- •On/Off ratio

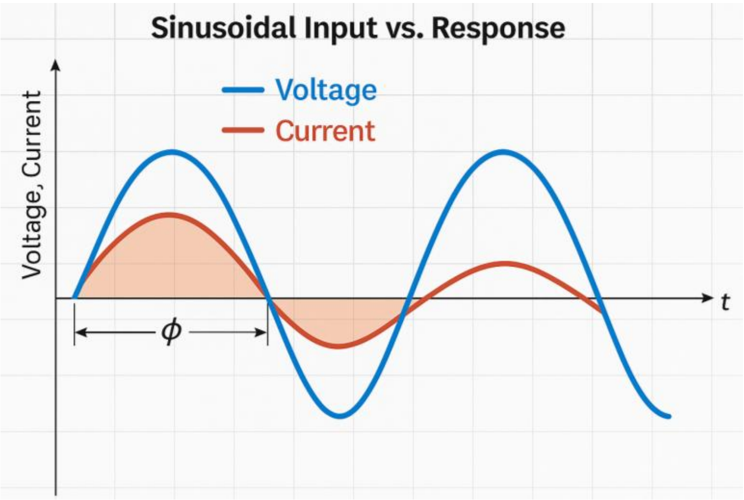
•Common Equipment:
- •Source Measure Units (e.g., Keithley 2400)
- •Semiconductor Parameter Analyzers (e.g., Agilent B1500A)
- •Probe Stations

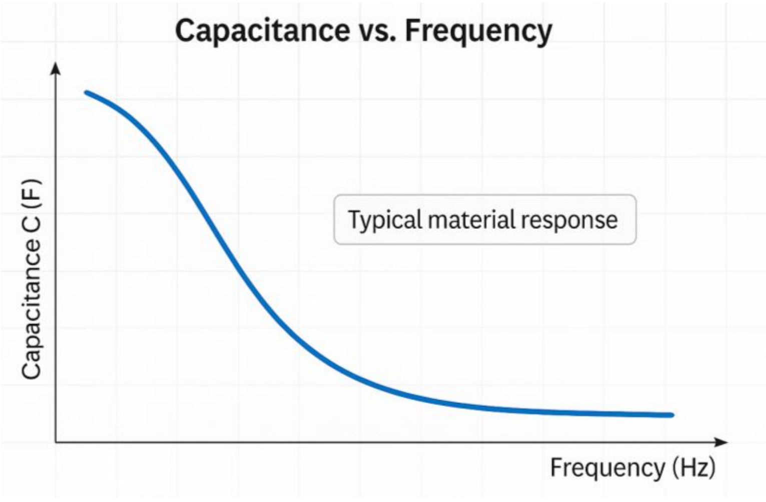


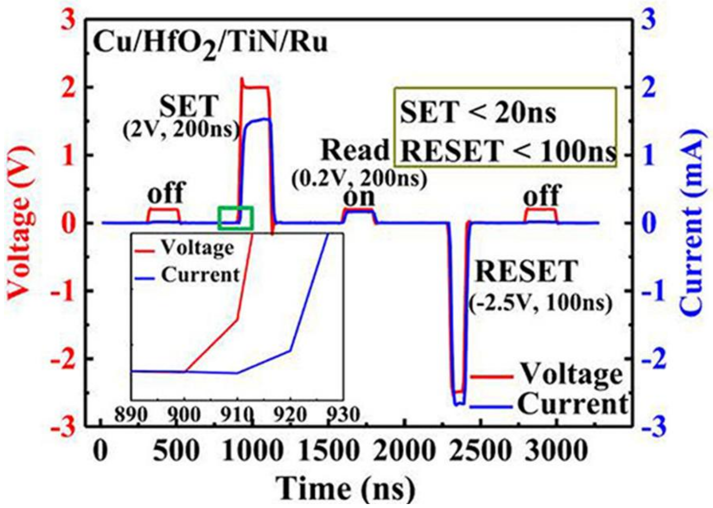
Sweeping voltage   Step-up voltage   Constant voltage

AC Measurements – Basics

What is AC (Alternating Current)?
•Electric signal that periodically **reverses direction**.
•Described by a **sinusoidal waveform** in most practical systems.
•Triangle and square pulses are also used in memory research.



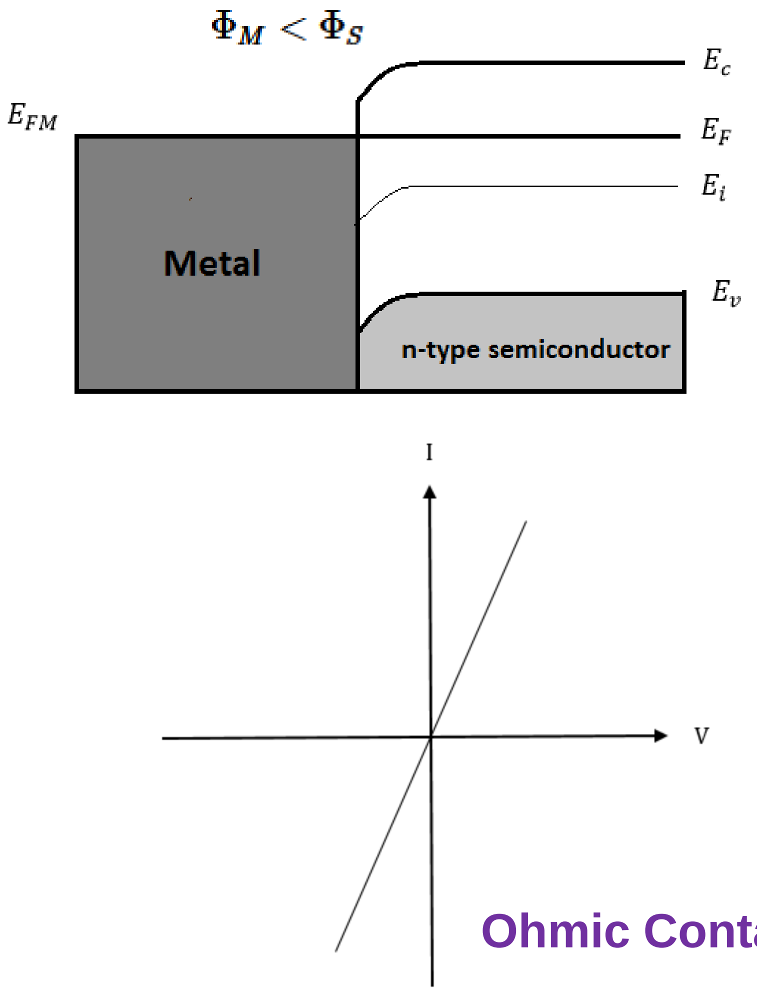




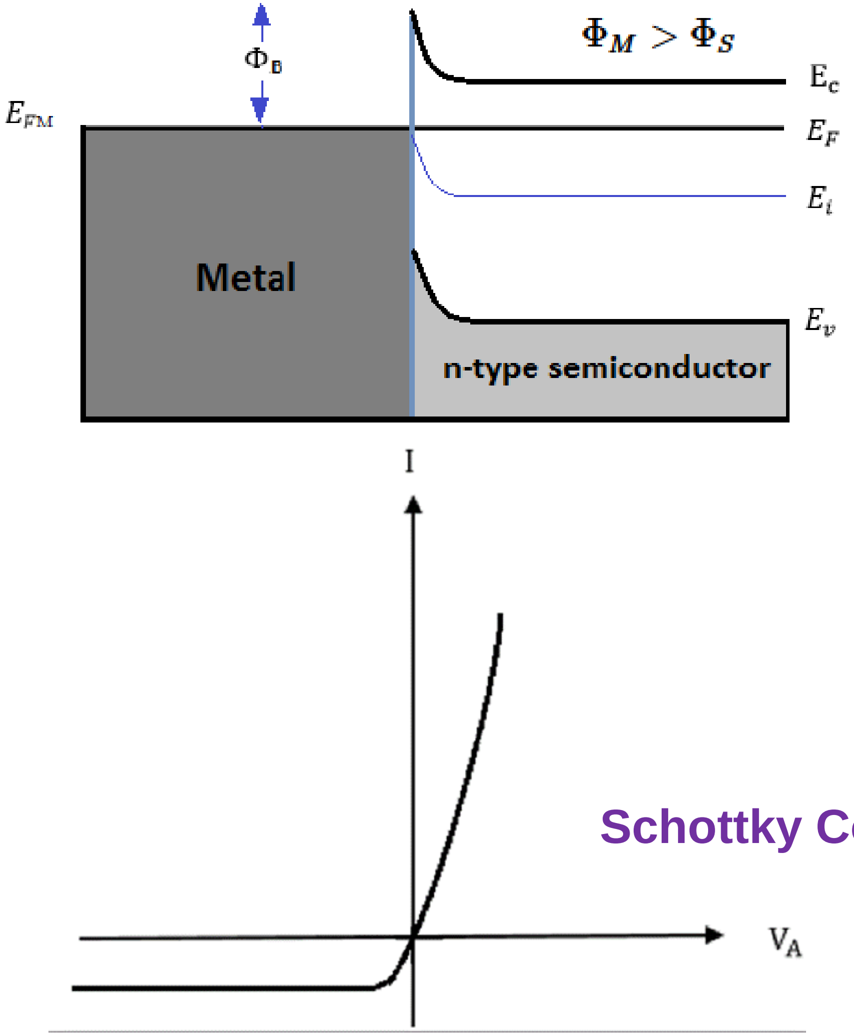
•**Basic Parameters Measured:**
- •Neuromorphic device parameters, EPSC, PPF, depression, potentiation.
- •Charge pumping, Trap evaluation
- •Dielectric constant, loss tangent
- •Capacitance (C), Inductance (L), Memristance (M)

I-V/C-V Characteristics…

Plot of current (I) vs. applied voltage (V); gives insight into conductivity, contact behavior, and nonlinearity.

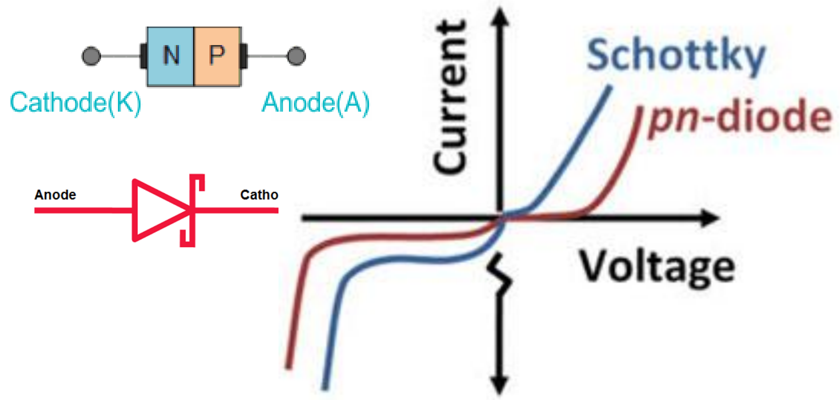


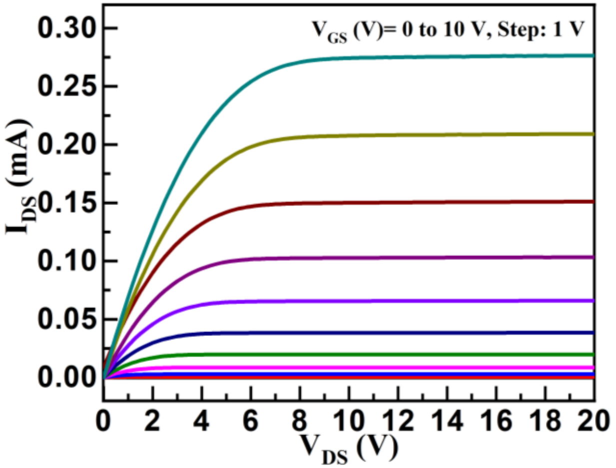
Ohmic Contact

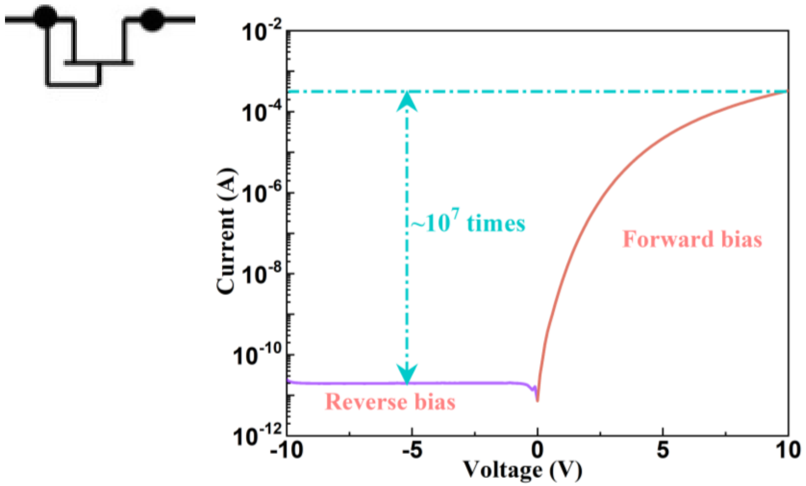


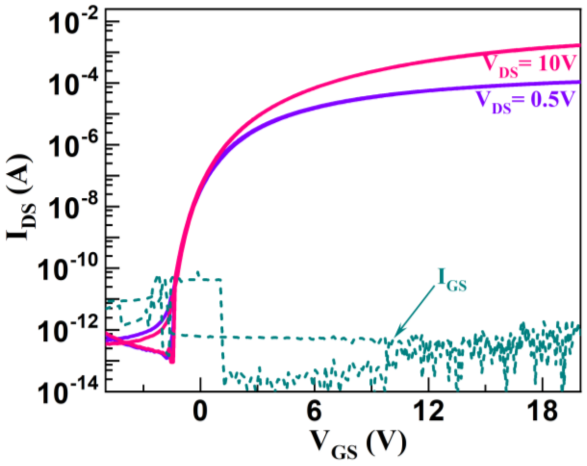
Schottky Contact

Example of I–V Characteristics









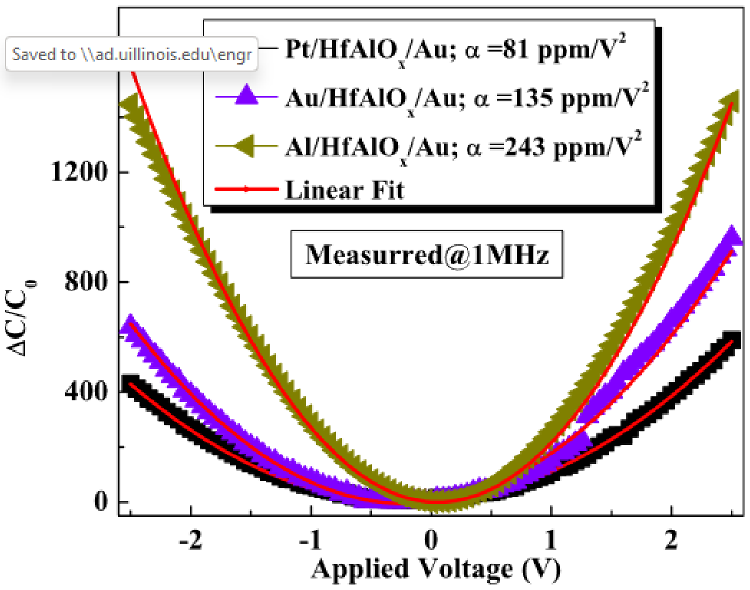
Extract Parameters:

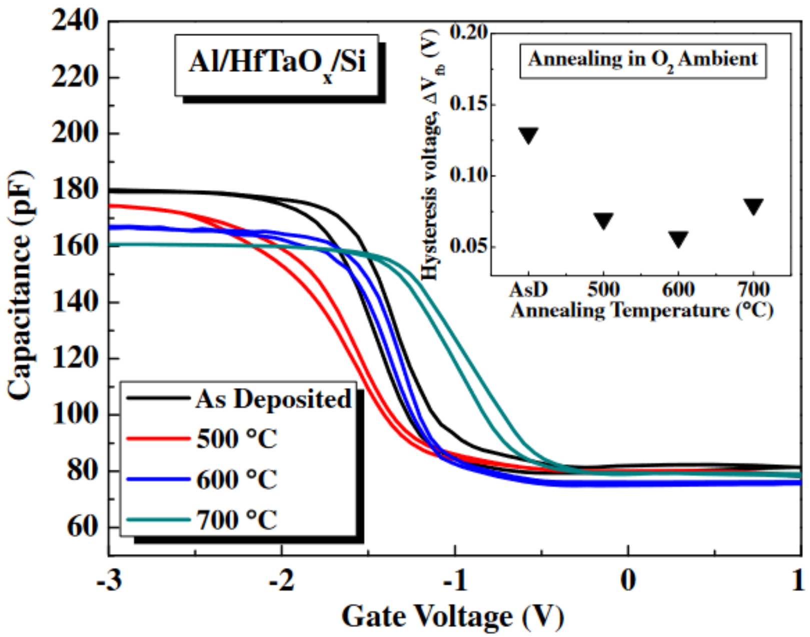
- From Diode
  - ✓ Knee voltage for diode
  - ✓ Breakdown voltage for diode
- From transistor:
  - ✓ Threshold Voltage (V_{th})
  - ✓ Turn On Voltage (V_{ON})
  - ✓ ON/OFF ratio
  - ✓ Subthreshold Swing (ss)
  - ✓ Mobility

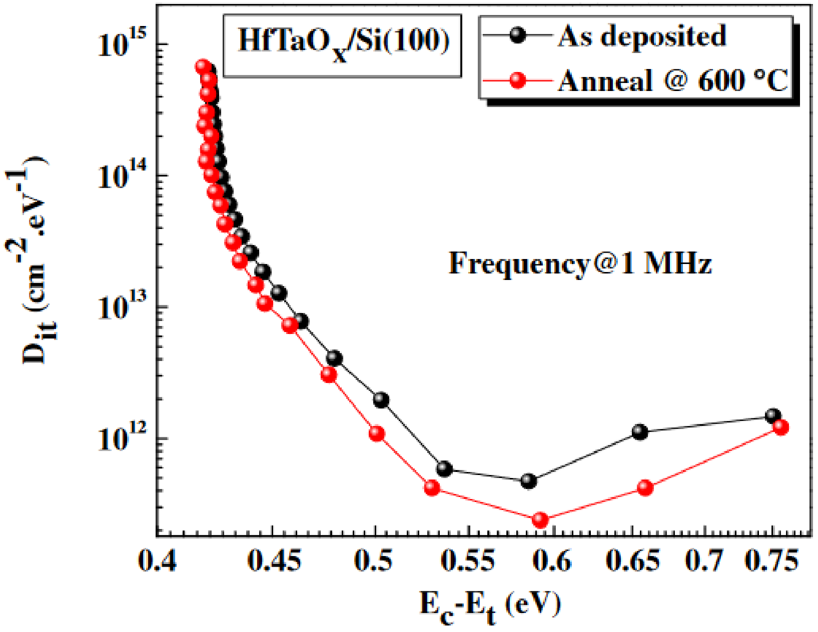
Example of Capacitance–Voltage (C–V) Characteristics

What is it? Apply an AC signal superimposed on a DC sweep to measure capacitance vs. voltage.

Why It's Used:
- Semiconductor doping profiling
- Depletion/inversion regions in MOS structures
- Interface trap density







Journal of The Electrochemical Society, 158 (2011) H44

Jpn. J. Appl. Phys. 50 (2011) 101101

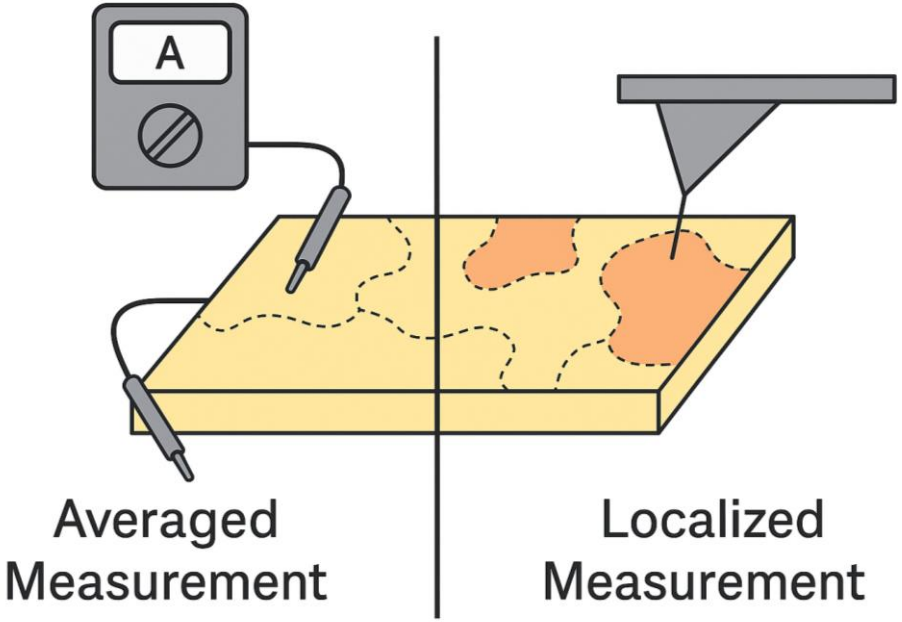
Electrical at local level

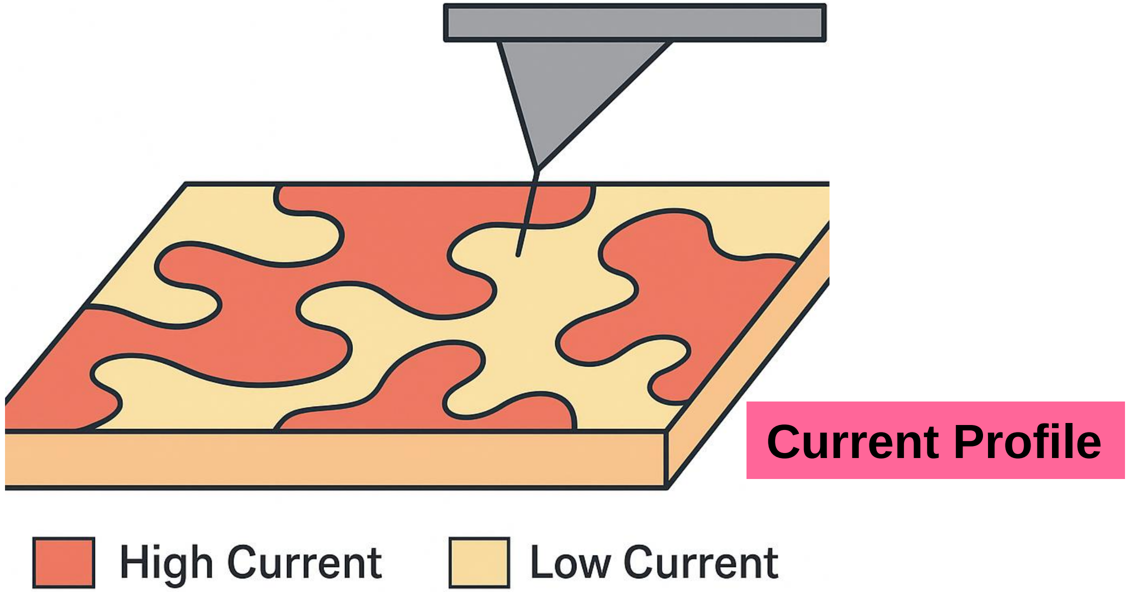
Electrical at the local level

Why "Local Level" Characterization?

•Traditional electrical measurements average out properties over large areas.
•**Local electrical characterization** targets **specific regions** (e.g., grains, interfaces, defects, junctions, layers) to:

- Understand **localized conduction paths**
- Diagnose **device failure points**
- Correlate **structure-property relationships**





Types of Local Electrical Characterization

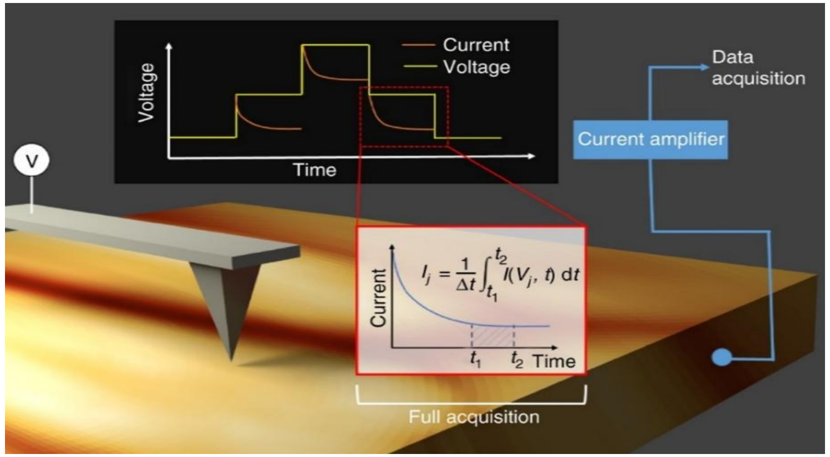
- **Conductive Atomic Force Microscopy (C-AFM)**
  - Principle: Measures local current flow through a conductive AFM tip.
  - Use: Mapping conductivity variations, identifying defects, and resistive switching sites.

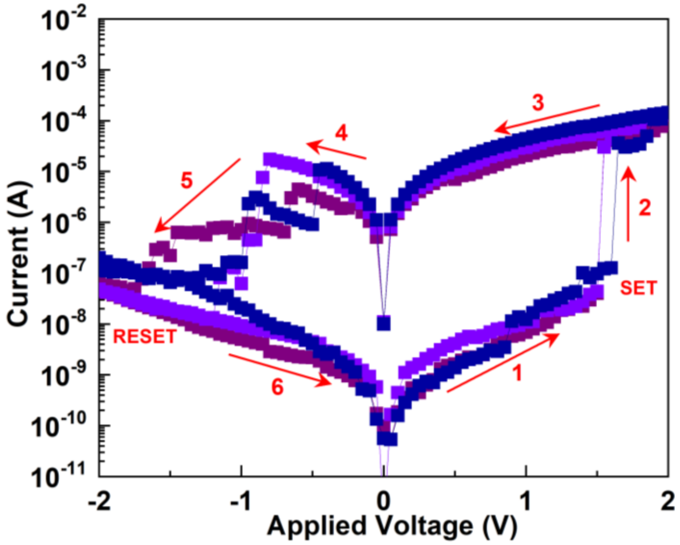
- **Scanning Tunneling Microscopy (STM)**
  - Principle: Measures tunneling current between a conductive tip and the sample.
  - Use: Imaging electronic states, surface structure of conductive materials.

- **Kelvin Probe Force Microscopy (KPFM)**
  - Principle: Measures local surface potential or work function.
  - Use: Studying charge distribution, surface dipoles, interface properties.

- **Piezoresponse Force Microscopy (PFM)**
  - Principle: Piezoresponse Hysteresis Loop measured at the local scale.
  - Use: Mapping ferroelectric domains, polarization switching.

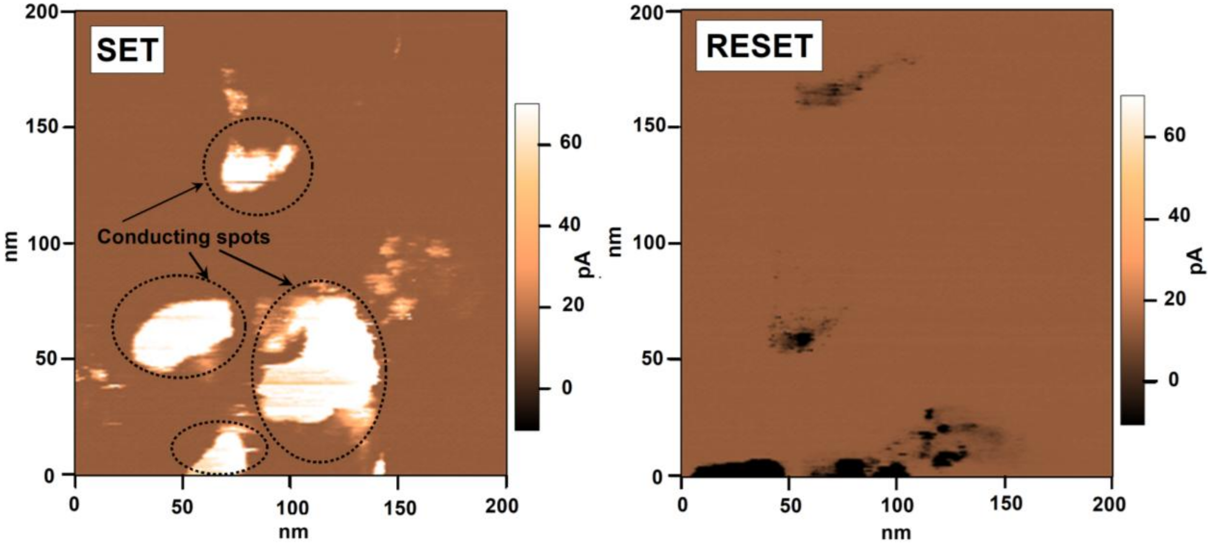
C-AFM for Memristors





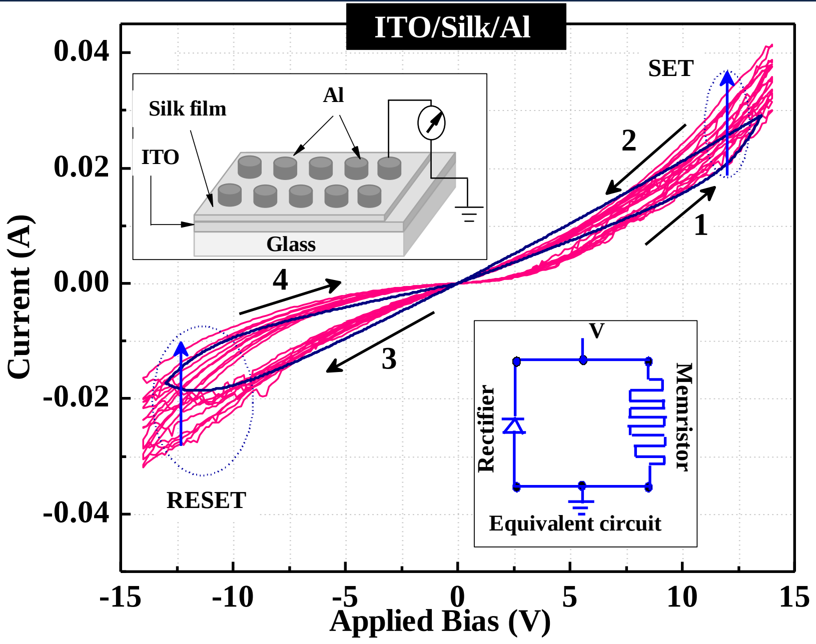
Asylum Research MFP-3D

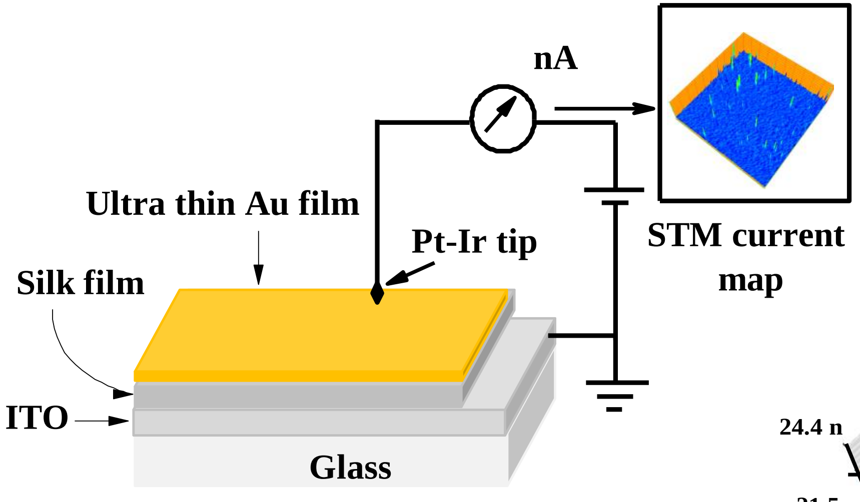
Nanosurf FlexAFM

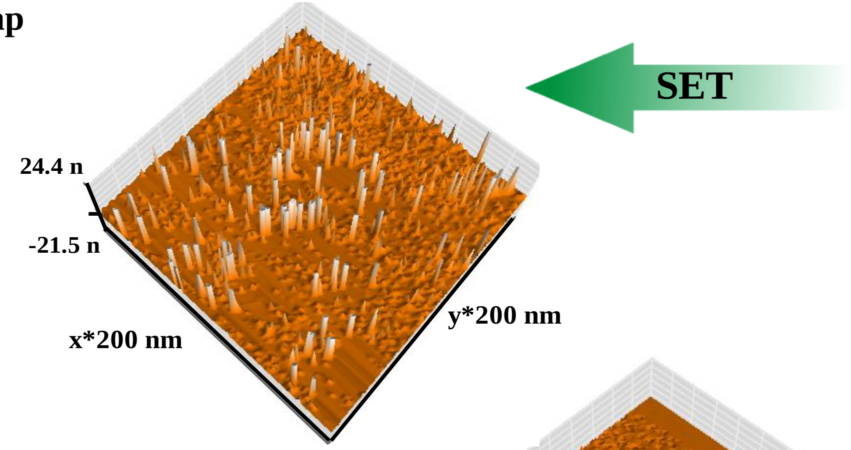


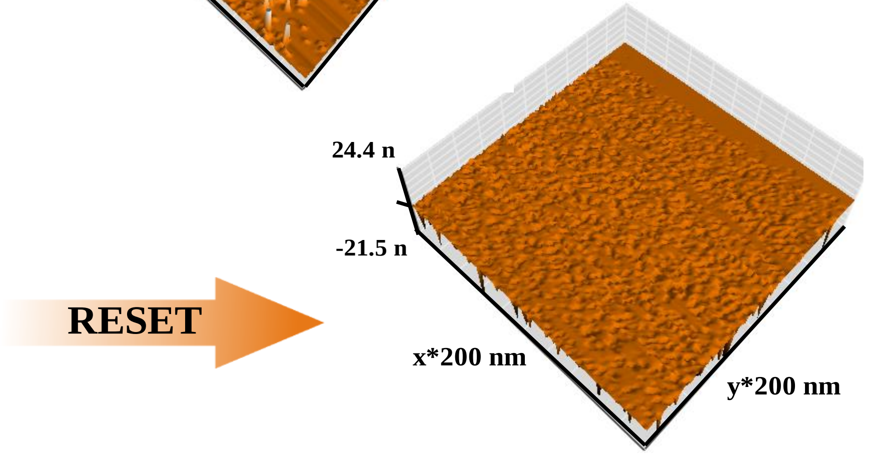
Adv. Electron. Mater. 1 (2015) 1400035

STM for Memristors









Nanosurf NaioSTM

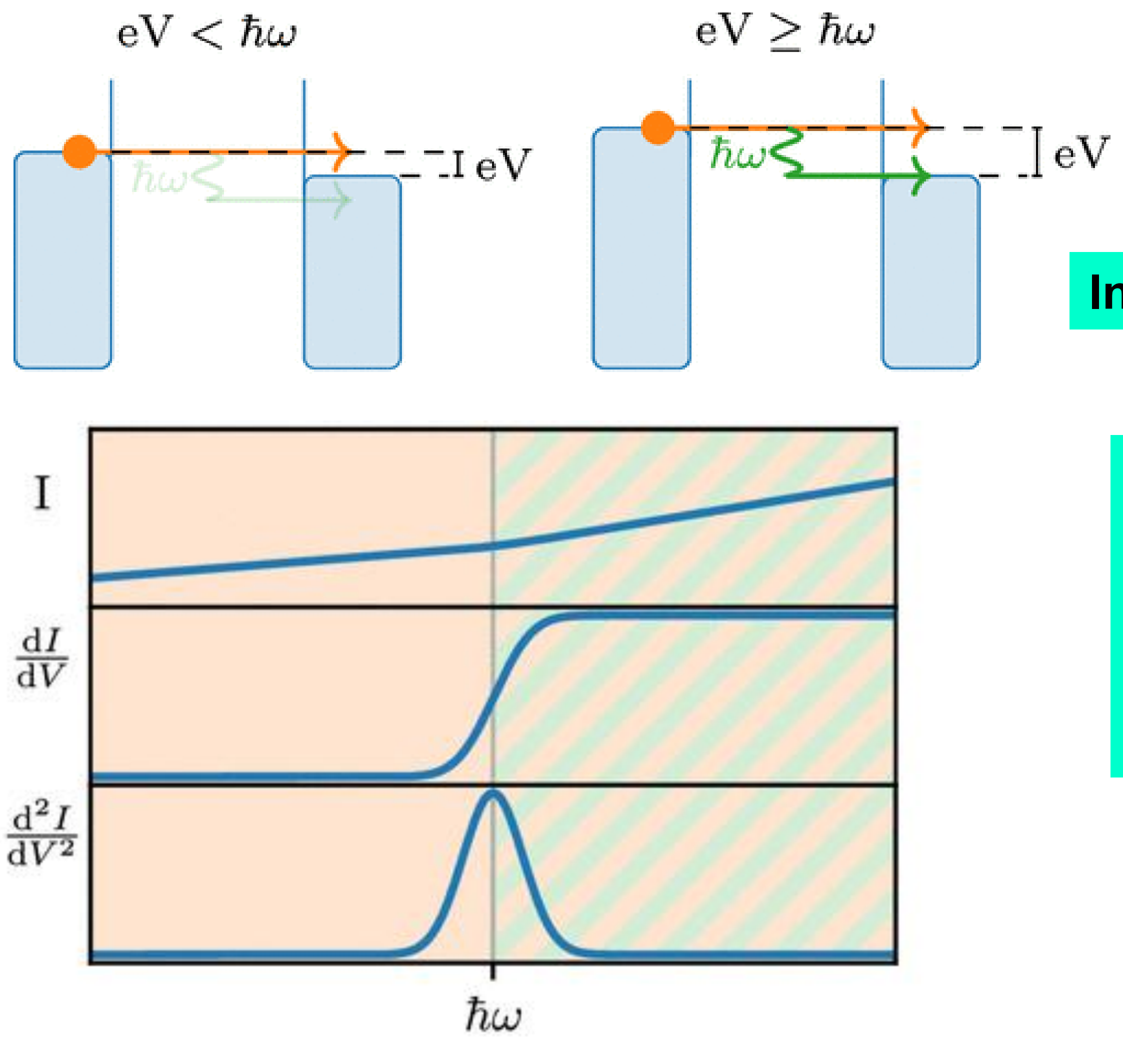
Adv. Funct. Mater. 22 (2012) 4493.

Inelastic Electron Tunneling Spectroscopy (IETS)

Inelastic Electron Tunneling Spectroscopy (IETS)

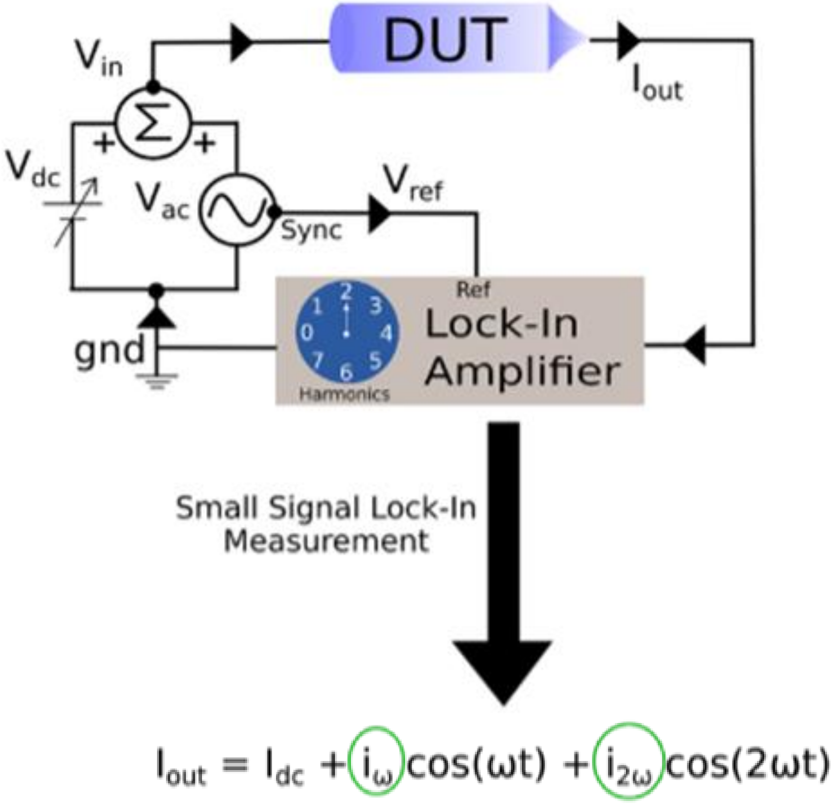
Elastic

Inelastic



- Identifying **chemical bonds** or **molecular species** in a tunnel junction,
- Revealing **interface chemistry** or **phonon interactions** in layered materials
- And probing **defect states** or **electron–phonon coupling**.

Measurement setup



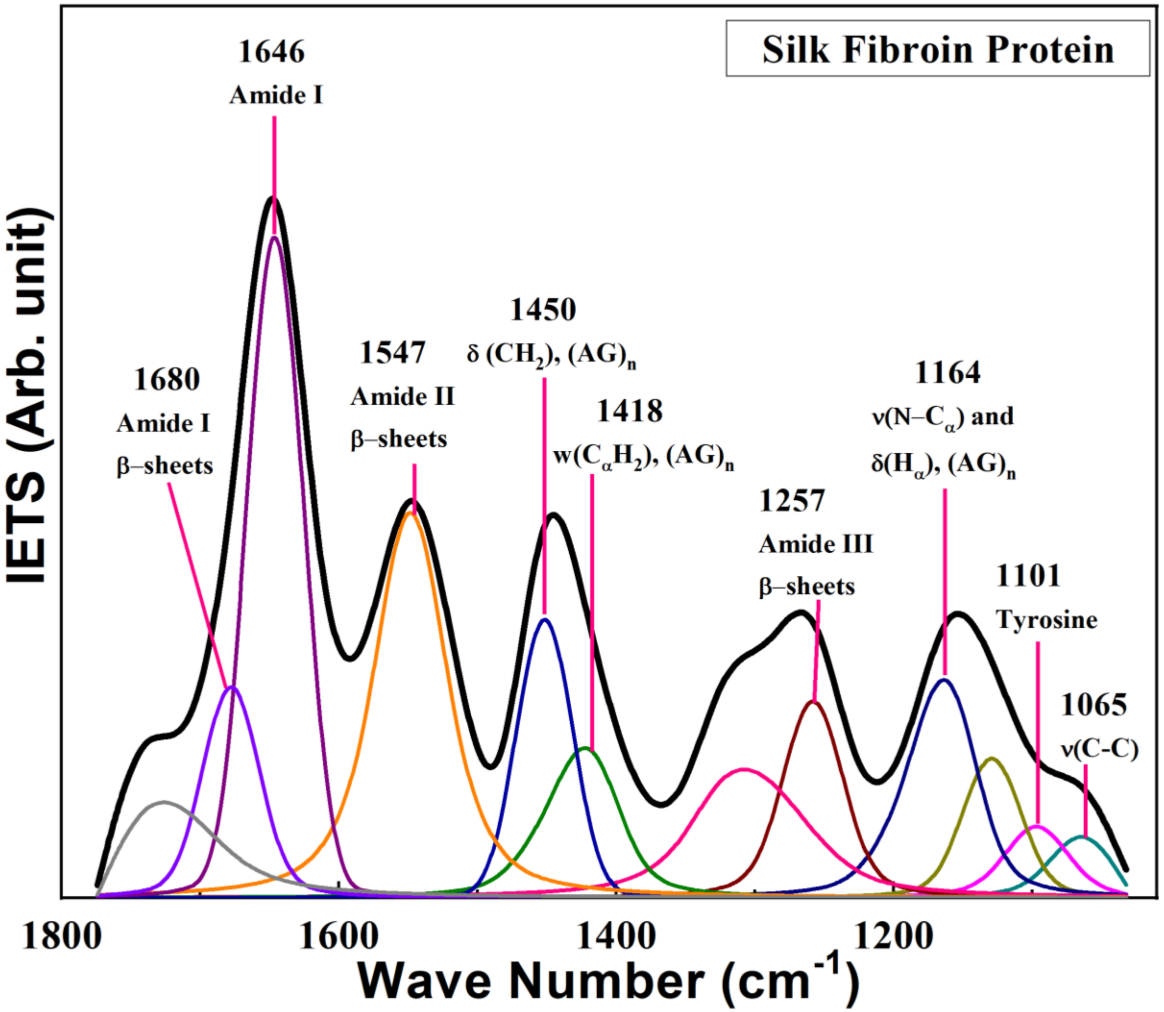
$$Wavenumber(cm^{-1}) = \frac{eV}{hc} \approx 8065.5 \times V$$

Essential Conditions for IETS

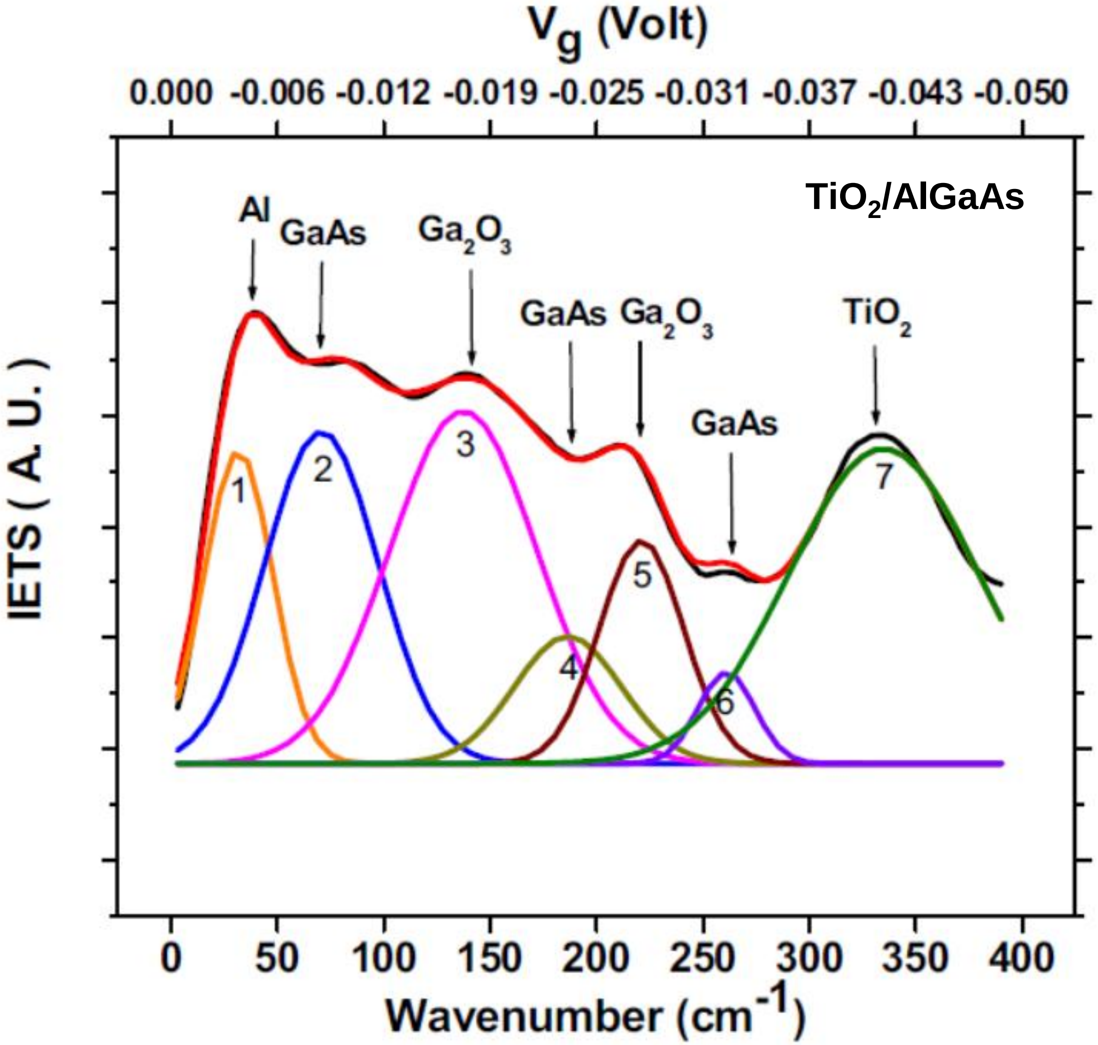
1. Ultrathin Insulating/Semiconducting Barrier
2. Metal–Insulator–Metal (MIM) Junction
3. Low Temperature
4. Low-Noise Measurement Setup
5. Lock-In Amplifier for d^2I/dV^2 Detection
6. Sharp and Symmetric I–V Characteristics

IETS signal: The amplitude of the 2nd harmonic component of the ac current

IETS Results

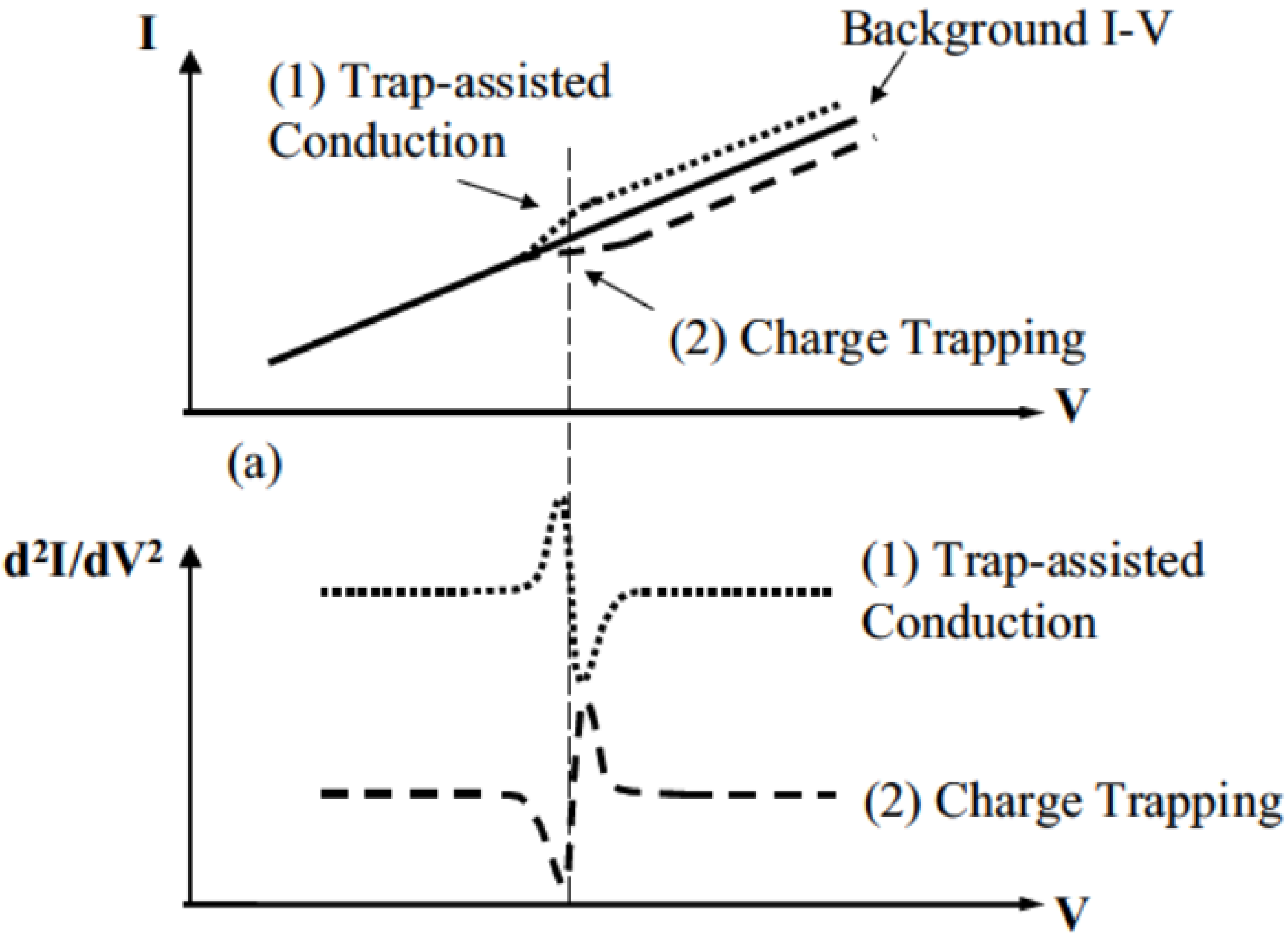


Phys. Status Solidi A 210, (2013) 1797

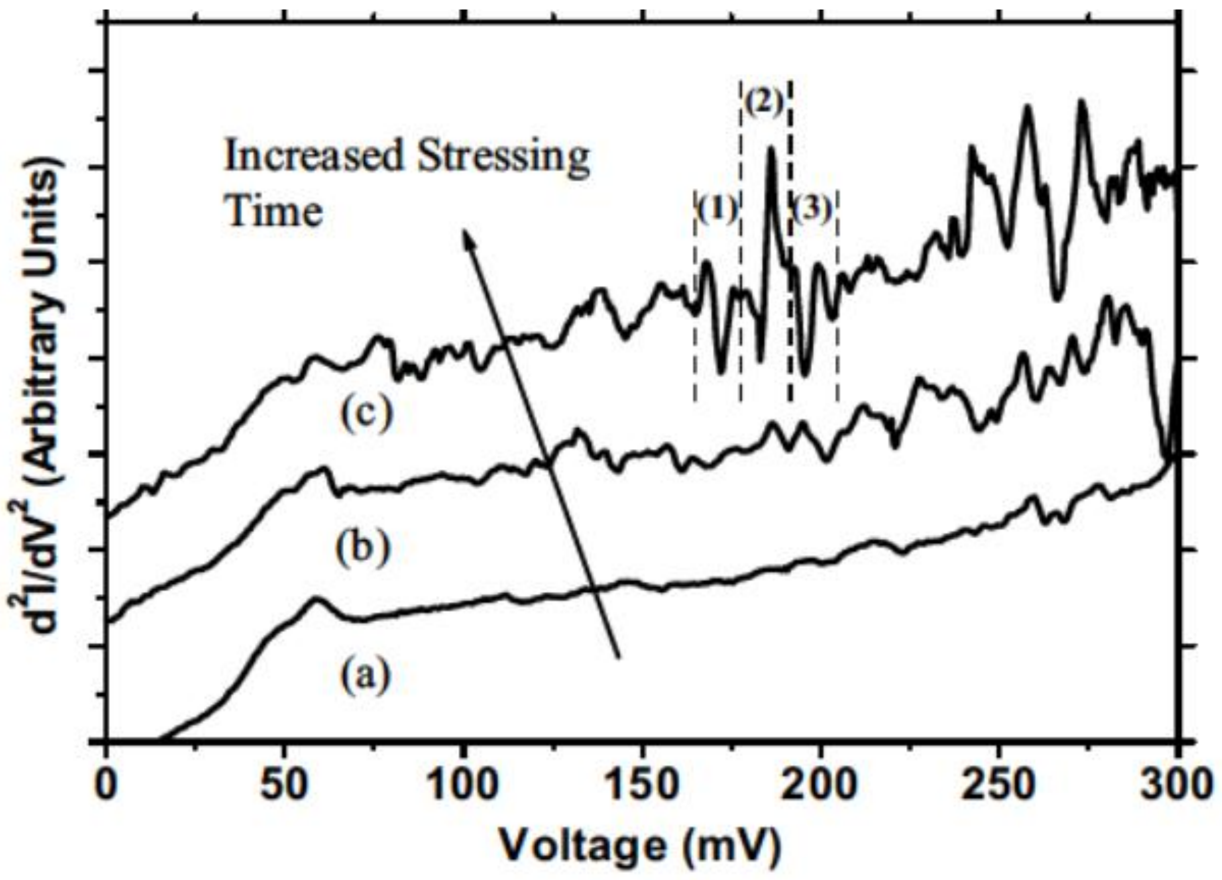


ECS Transactions, 35 (2011) 545.

IETS: Traps Evaluation

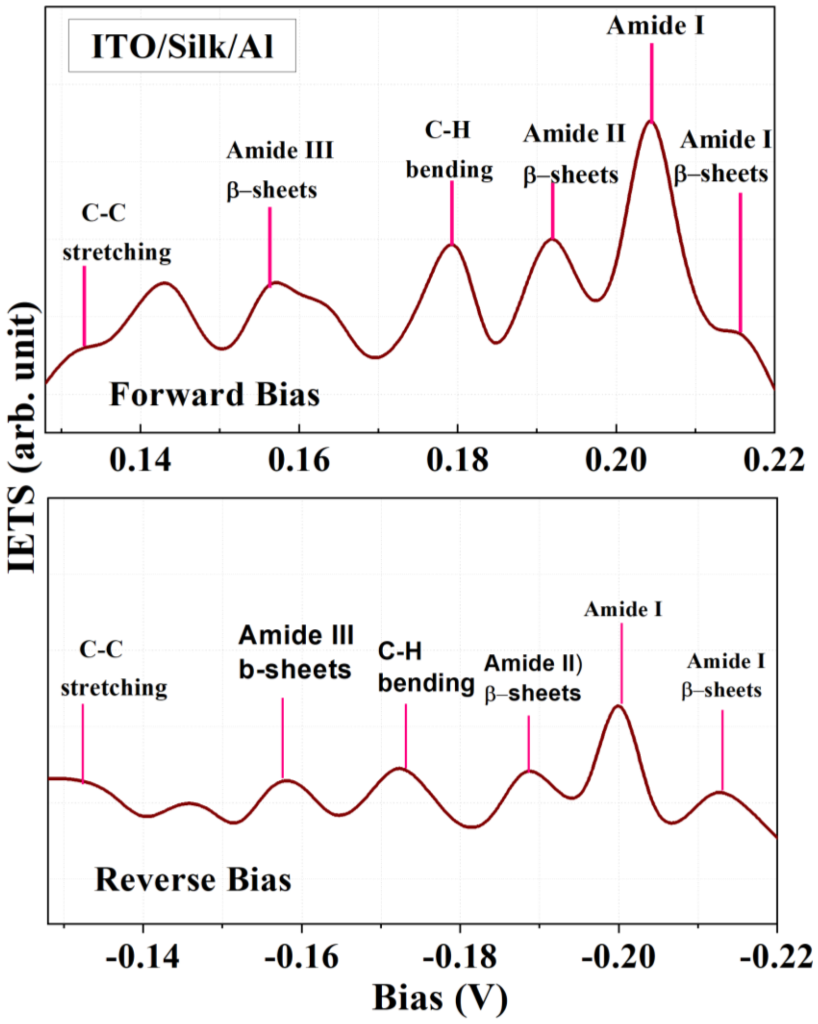


Example: Traps



(1) Trap-assisted conduction
(2) -(3) Charge trapping

ECS Transactions, 35 (2011) 545.



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Final Thoughts

As materials and devices grow more complex, our characterization tools must evolve—not just in precision, but in intelligence.

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