Hall Effect Measurements for Semiconductor and Other Material Characterization

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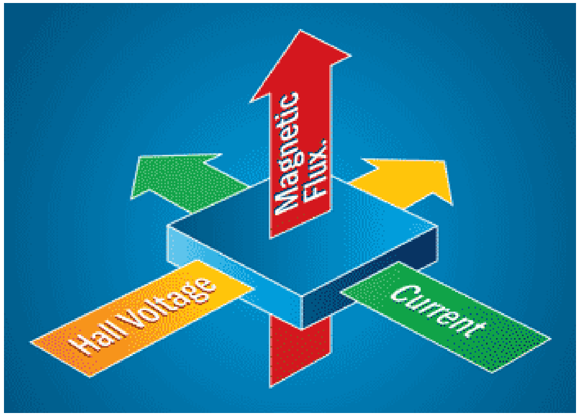
Seminar Overview

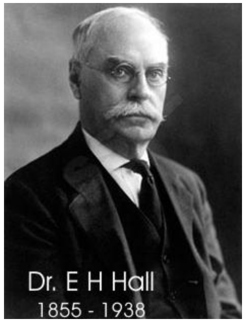
- What are Hall effect measurements?
- Industry trends driving the need for Hall effect measurements
- Key considerations when selecting equipment for Hall effect measurements
- Measurement techniques

Hall Effect Measurement Overview

- A Hall effect measurement system is used to measure a material's electrical properties such as:
  - Carrier mobility (μ) and concentration (n)
  - Hall voltage (V_H)
  - Hall coefficient (R_H)
  - Resistivity (ρ)
  - Magnetoresistance (R_B)
  - Conductivity Type (N or P)
  - I-V curves (optionally)



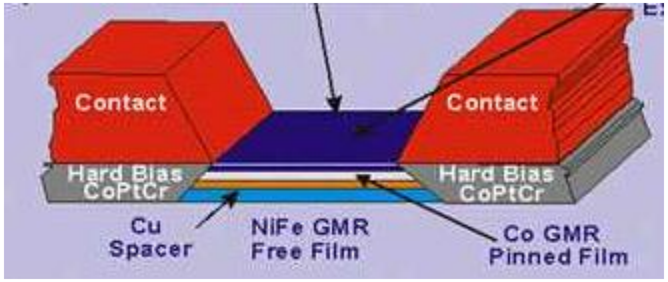
- The Hall effect refers to the potential difference (Hall voltage) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current. Edwin Hall discovered this effect in 1879. http://en.wikipedia.org/wiki/Hall_effect



Materials Types

The Hall Effect is used to measure:

- Semiconductor materials such as Si, Ge
- Most compound semiconductor materials including pHEMTS, SiGe, SiC, GaAs, AlGaAs, InAs, InGaAs, InP, AlGaAs, and CdTe HgCdTe (including thin films for solar cell/photovoltaics)
- Organic semiconductors and nano-materials
- Low resistance materials including metals, transparent oxides, highly doped semiconductor materials, high temperature superconductors, dilute magnetic semiconductors, GMR/TMR materials, and graphene-based materials
- High resistance semiconductor materials including semi-insulating GaAs and GaN, and CdTe



Why the Resurgence in People Doing Hall Effect? Some “Simple” Math…

$$I = \frac{V}{R} = \frac{V}{\frac{\rho L}{A}} = \frac{VA}{\rho L} = \frac{qn\mu VA}{L}$$

I = Current (A)
V = Voltage (V)
R = Resistance of sample (Ω)
ρ = Resistivity of sample (Ω-cm)
L = length of sample (cm)
A = cross sectional area of sample (cm^2)

For a doped semiconductor:

$$\rho = \frac{1}{qn\mu}$$

q = Electron charge (C/cm^2)
n = Carrier carrier concentration (cm^{-3})
μ = Carrier mobility ($\text{cm}^2\text{/Vs}$)

Why the Resurgence in People Doing Hall Effect? Some "Simple" Math…

n = electron carrier density (cm^{-3})

μ = electron mobility (cm^2/Vs)

V = voltage applied (V)

L = length of sample (cm)

A = cross sectional area of sample (cm^2)

$$I = \frac{qn\mu VA}{L}$$

- To increase I (higher drive current, faster switching, etc.)
  - Increase voltage, V,
  - Increase number of electrons, n
  - Increase area of sample, A
  - Increase mobility of electrons, μ

The Goal: Maximizing Current Flow

n = electron carrier density (cm^{-3})

μ = electron mobility (cm^2/Vs)

V = voltage applied (V)

L = length of sample (cm)

A = cross sectional area of sample (cm^2)

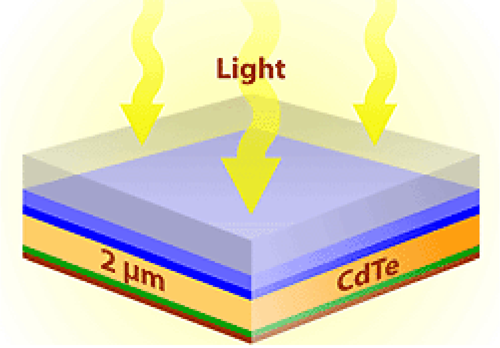
$$I = \frac{qn\mu VA}{L}$$

- To increase I (higher drive current, faster switching, etc)
  - Increase voltage, V
  - Increase number of electrons, n
  - Increase area of sample, A
  - Increase mobility of electrons, μ ✓

Becoming more difficult

Hall Effect Measurements are the Quantitative Tool for Determination of Mobility on New Materials

- Can no longer just keep shrinking devices to get performance
  - Moore's Law collides with photolithography limits
- Therefore, materials are no longer just Si
  - People adding Ge to Si to strain lattice to get higher mobility µ
- Materials are no longer bulk
  - Thin films like in CIGS solar cells
  - Single-atom layer materials, Graphene

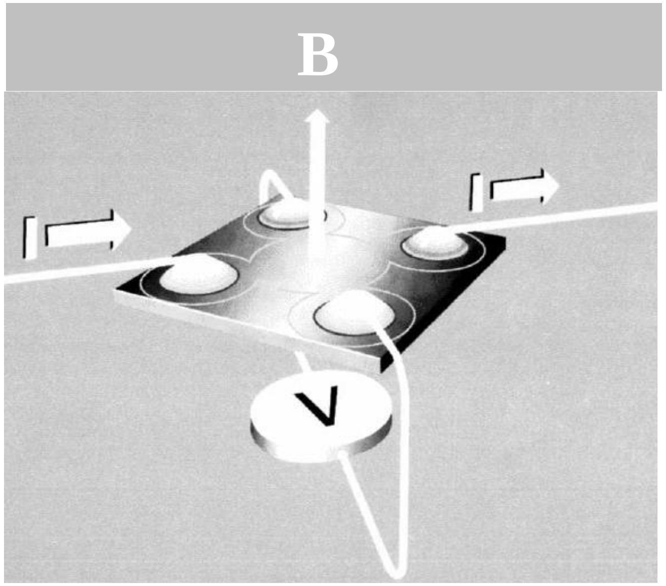


- **HALL effect measurement derives µ**

$$I = \frac{qn\mu VA}{L}$$

How to Measure Mobility, μ, Using Hall Effect Techniques Overview

- First measure Hall Voltage, V_H
  - Force magnetic field B
  - Source I
  - Measure V_H
  - t is sample thickness
- Next, measure resistivity, ρ
  - Use the van der Pauw technique
- Then calculate Hall mobility, μ_H:



$$\mu_H = \frac{|V_H t|}{BI\rho}$$

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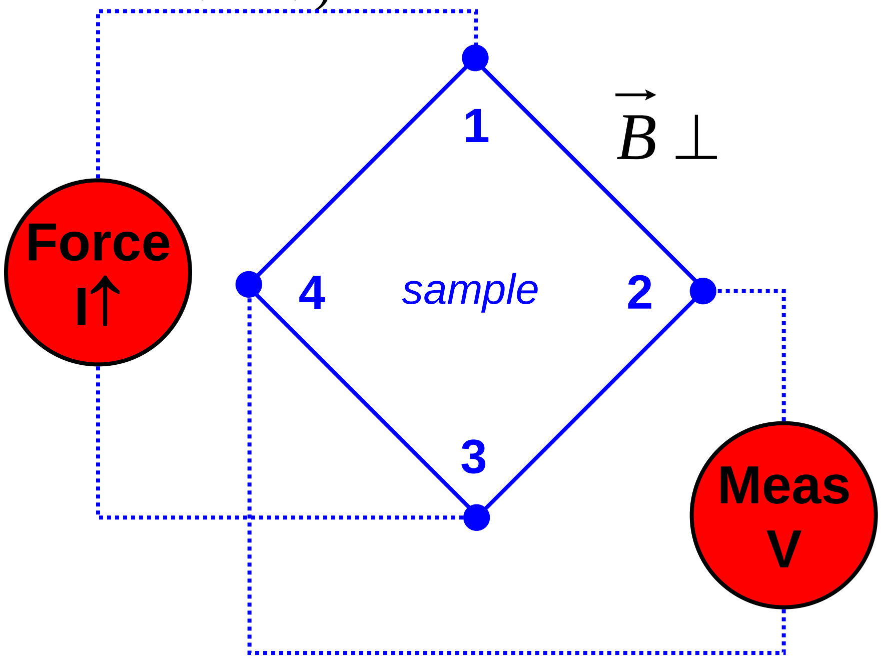
How to Measure Mobility, μ, Using Hall Effect Techniques Measurement Configuration

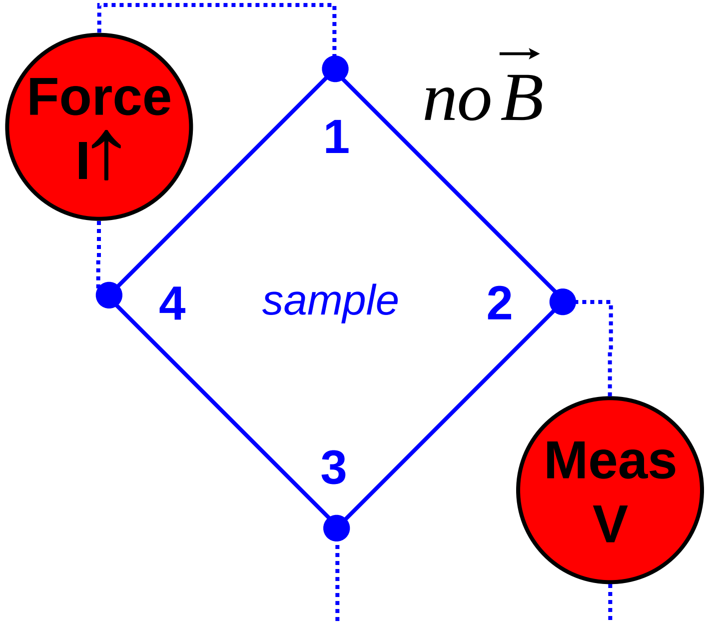
Hall Effect:

- Force I on ***opposite*** nodes
- Meas V on the other opposite nodes
  - V typically ~ nV – V (typically uV-mV)

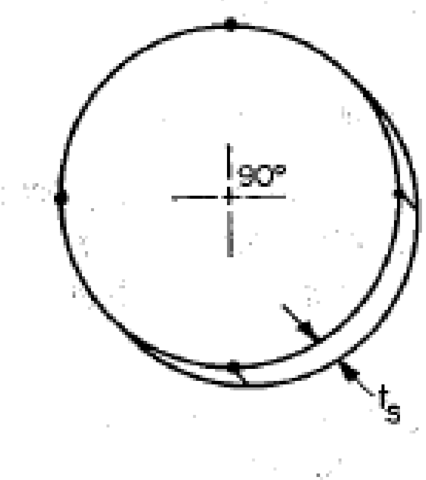


van der Pauw resistivity:

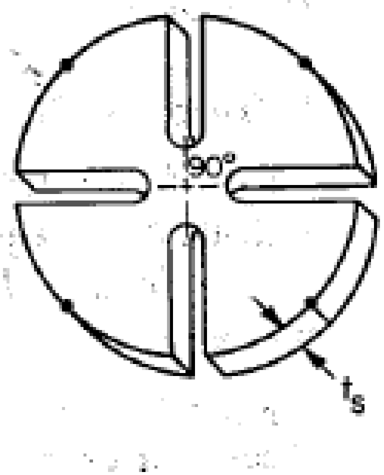
- Force I on ***adjacent*** nodes
- Meas V on the opposing adjacent nodes
  - V should be <5V, typically mV
- Gives ρ so that μ can be calculated



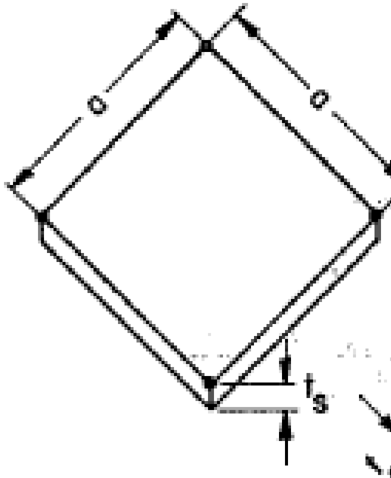
ASTM Recommended Sample Specimens for Hall Effect and van der Pauw Measurements



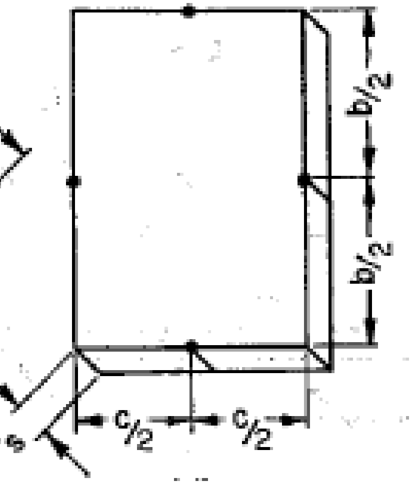
Circle



Clover Leaf



Square



Rectangle

Recommended sample thickness is ≤ 0.1cm

Reference: ASTM F76

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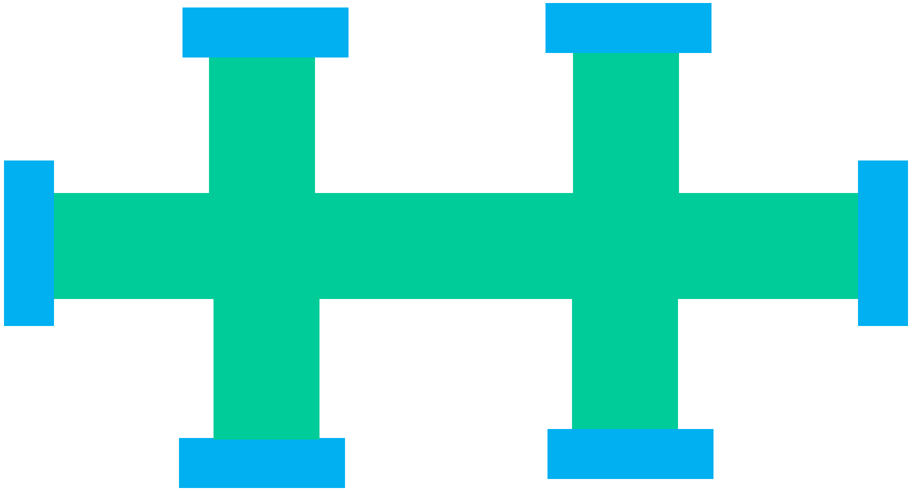
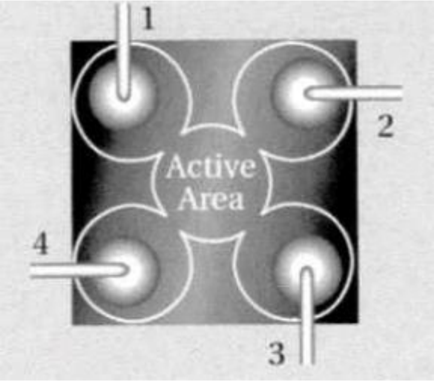
Additional ASTM Sample Geometries Bridge-Type or Hall Bar Configurations



Typical configuration used by graphene researchers

Reference: ASTM F76

Good Sample Preparation Technique Ensures Good Measurements



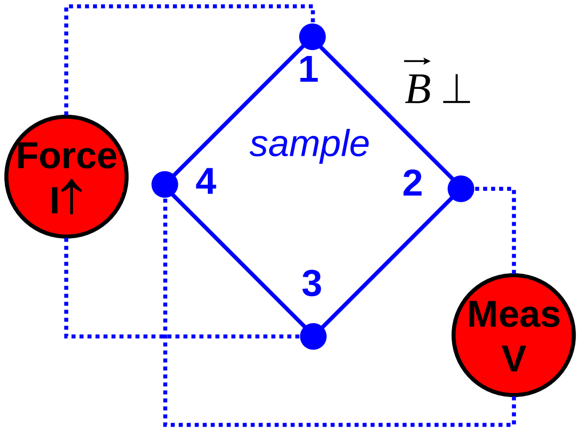
- Ohmic contact quality, symmetry, and size
- Sample uniformity
- Accurate knowledge of thickness
- Temperature uniformity
- Photoconductive and photovoltaic effects

How to Measure Mobility, μ, Using Hall Effect Techniques
Determining an Accurate V_H

www.nist.gov/eeel/

1. Apply a Positive magnetic field B

2. Force a current I_{13} to leads 1 and 3 and measure V_{24P}
3. Force a current I_{31} to leads 3 and 1 and measure V_{42P}
4. Likewise, measure V_{13P} and V_{31P} with I_{42} and I_{24}, respectively
5. Reverse the magnetic field (Negative B)
6. Likewise, measure V_{24N}, V_{42N}, V_{13N}, and V_{31N} with I_{13}, I_{31}, I_{42}, and I_{24}, respectively
7. Calculate Hall voltage, V_H



Changing connections during Steps *4* & *6* → automate with a switch matrix

Especially if sample is in a liquid nitrogen dewar

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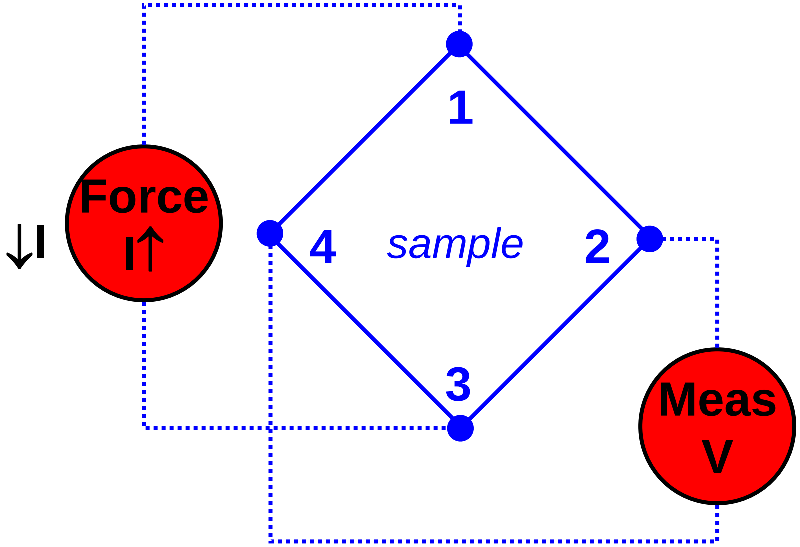
Computing the Hall Voltage

$$V_C = V_{24P} - V_{24N}$$

$$V_D = V_{42P} - V_{42N}$$

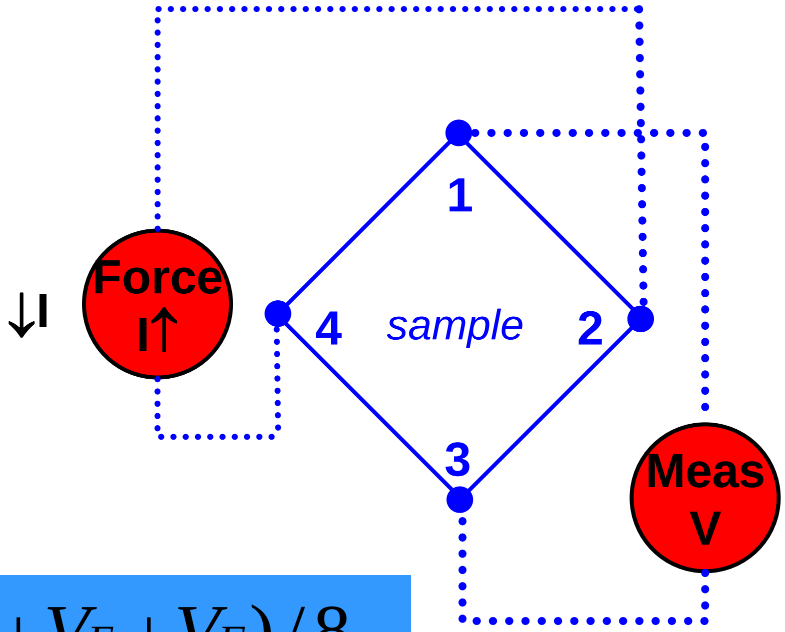
$$V_E = V_{13P} - V_{13N}$$

$$V_F = V_{31P} - V_{31N}$$



$$\bar{B} \perp$$

$$B \top$$

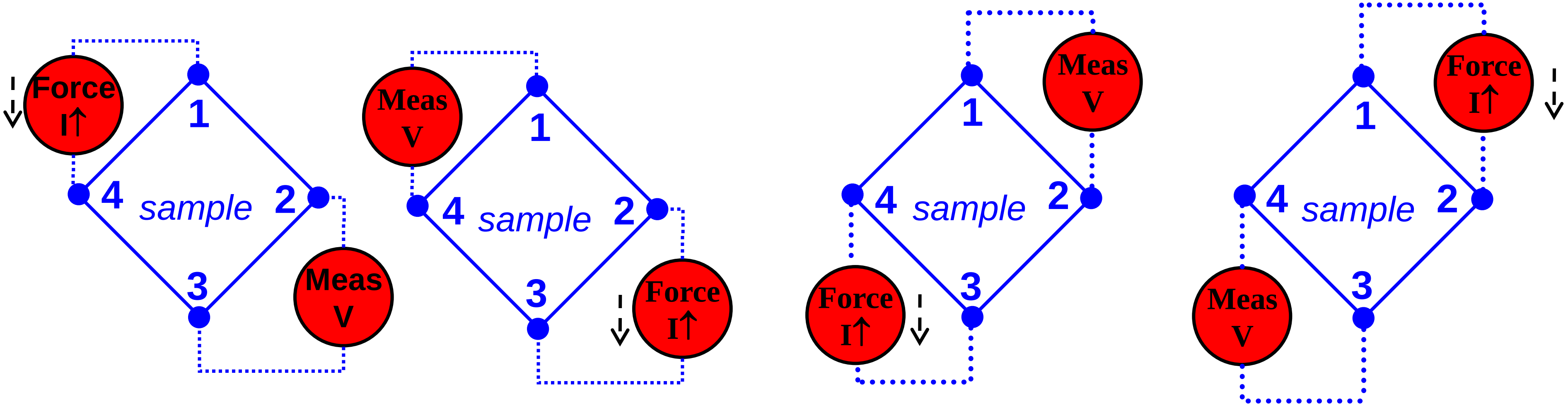


$$V_H = (V_C + V_D + V_E + V_F)/8$$

Computing Resistivity, ρ, with the van der Pauw Measurement

$R_{14,23} = V_{23} / I_{14}$ $R_{23,14} = V_{14}, I_{23}$ $R_{43,12} = V_{12} / I_{43}$ $R_{12,43} = V_{43} / I_{12}$

$R_{41,32} = V_{32} / I_{41}$ $R_{32,41} = V_{41} / I_{32}$ $R_{34,21} = V_{21} / I_{34}$ $R_{21,43} = V_{34} / I_{21}$



$$R_A = (R_{21,34} + R_{12,43} + R_{43,12} + R_{34,21}) / 4$$

$$R_B = (R_{32,41} + R_{23,14} + R_{14,23} + R_{41,32}) / 4$$

$$e^{(-\pi R_A / R_S)} + e^{(-\pi R_B / R_S)} = 1$$

If $R_A = R_B = R$

then $R_S = \dfrac{\pi}{\ln 2} R$

$$\rho = R_S \bullet t$$

Final Computation to Determine Hall Mobility

$$\mu_H = \frac{|V_H t|}{BI\rho}$$

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Hall Effect Equipment List
Measurement Equipment

- Constant-current source, magnitude depends on sample resistance
  - Low resistance material (mA to A)
  - Semi-insulating GaAs, $\rho \sim 10^7 \Omega\cdot$cm, a range as low as 1nA is needed
  - High resistance (intrinsic semiconductors) (nA to pA)

- Voltmeter covering 1µV to 100V
  - Required range depends on material resistivity
  - High resistivity materials may need ultra-high input Z or differential measurement

- Optional:
  - Switch matrix to eliminate manual connection and disconnection
  - Temperature measurement instrument
    - Sample temperature-measuring probe (resolution of 0.1°C for high accuracy work)

Hall Effect Equipment List

Magnetic Field Generation, Sample Holder, and Environmental Control

- Magnet:
    - Fixed/permanent magnet or electromagnet
        - 500 to 5000 gauss

- Prober with manipulators and probe tips

- If doing temperature studies:
    - Appropriate prober chuck or oven
    - Temperature controller
    - Cryostat for holding samples if low-temperature

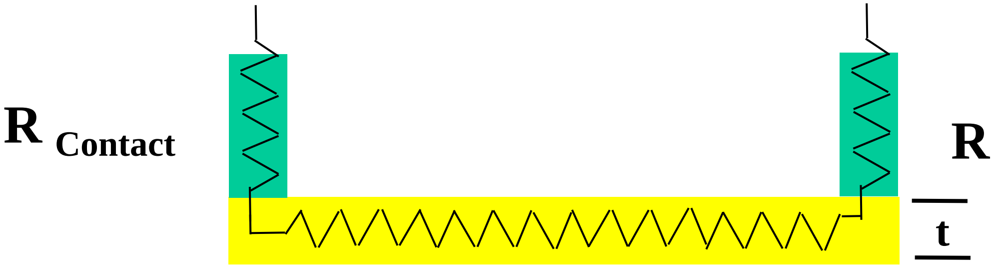
Other Equipment Needed
Other Measurements

- A more general research lab will want Hall effect and more:
  - Collinear resistivity measurements
  - Full I-V sweeps
  - C-V measurements
  - Transient response studies

- So "other equipment" list may include complementary equipment (hardware and software) not just for Hall effect but related measurements

Selecting the Correct Measurement Equipment Based on Sample's Total Resistance

- Total Resistance is Sample Resistance + Contact Resistance
  - Sample Resistance → value is primarily based on sample's resistivity, ρ, & sample's thickness, t
  - For square sample, sample resistance R = ρ/t
- Contact resistance at metal-semiconductor interface (some nominal approximations):
  - GaAs : Contact resistance ~ 1000 * sample resistance
  - For Si, Contact resistance ~ 300 * sample resistance

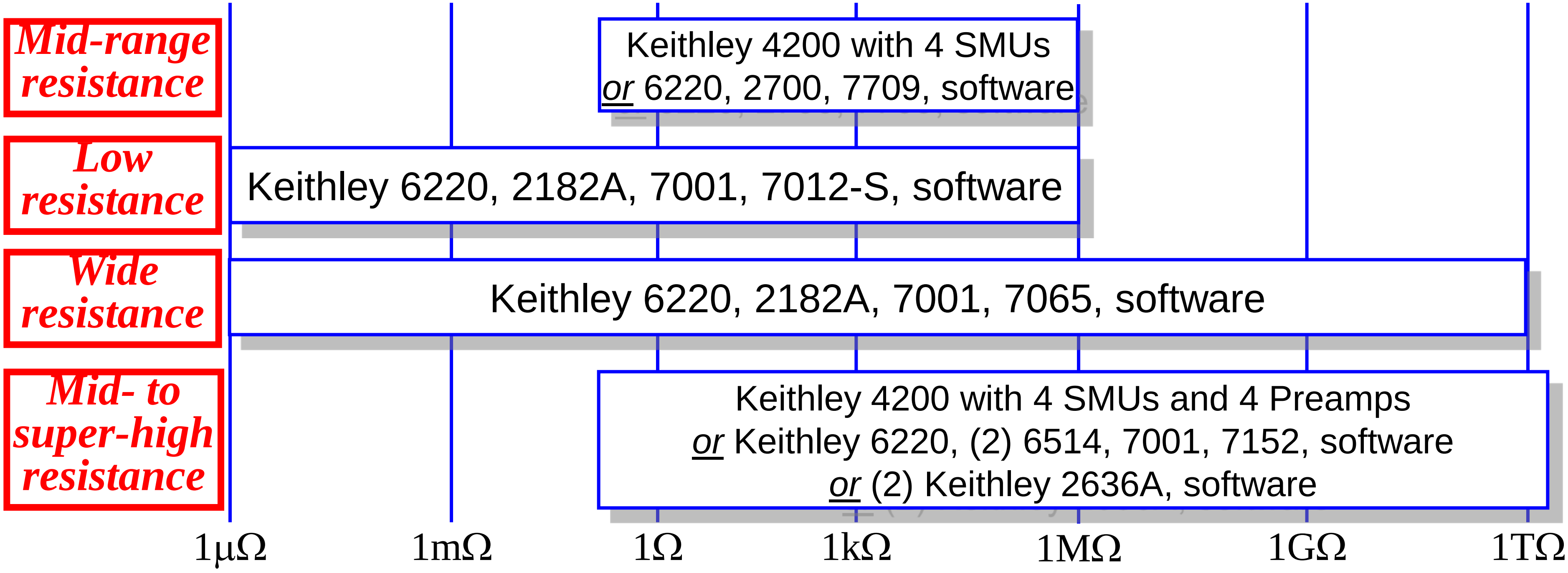


$$R_{sample}=\rho/t$$

Selecting the Correct Measurement Equipment Based on Sample's Total Resistance

- Representative ranges:
  - Mid-range resistance
    - Typically: Nominally doped Si or Ge (~10^{15} cm^{-3}); Si photvoltaics; pHEMTS; ITO
  - Low resistance
    - Typically metals, highly doped Si or Ge (>10^{17} cm^{-3}); SiGe; superconductors; GMR/TMR
  - Low-to-high (wide range) resistance
    - Typically thin film photovoltaics like CIGS, CdTe, HgCdTe
  - Mid- to super-high resistance
    - Typically GaAs, GaN, InP, InGaAs, AlGaAs, SiC, semi-insulating Si or CdTe

Overview of Instrumentation Solutions



Mid-range resistance

Keithley 4200 with 4 SMUs
or 6220, 2700, 7709, software

Low resistance

Keithley 6220, 2182A, 7001, 7012-S, software

Wide resistance

Keithley 6220, 2182A, 7001, 7065, software

Mid- to super-high resistance

Keithley 4200 with 4 SMUs and 4 Preamps
or Keithley 6220, (2) 6514, 7001, 7152, software
or (2) Keithley 2636A, software

Sample Resistance (Ω)

(actual selection depends on Total Resistance = Sample Resistance + Contact Resistance)
Sample Resistance ≈ ρ/t

Hall Effect Measurement Equipment

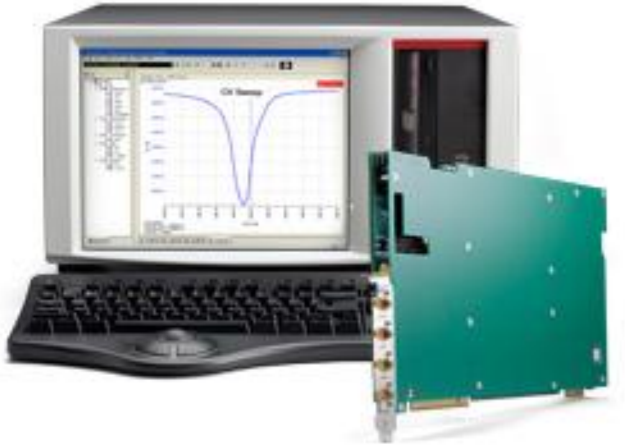
- **Mid-range resistance**
  - **100 mΩ to 1 MΩ**
    - **Typically: Nominally doped Si or Ge (~10^{15} cm^{-3}); Si photvoltaics; pHEMTS; ITO**
- **Low resistance**
- **Low-to-high (wide range) resistance**
- **Mid- to super-high resistance**

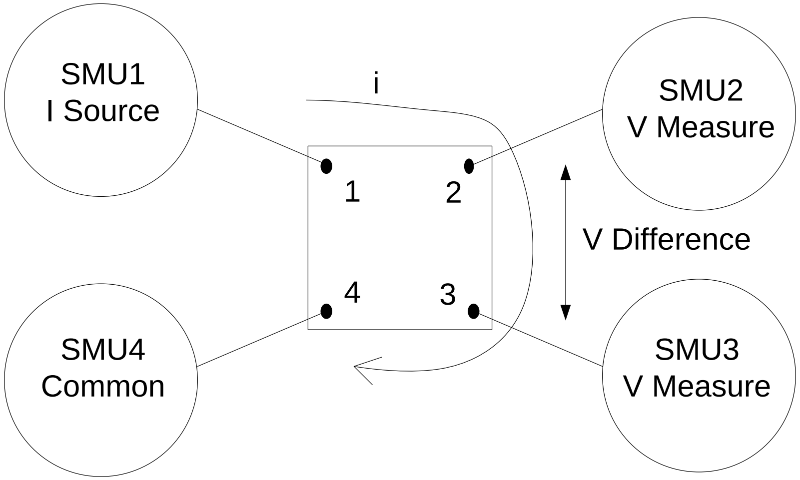
Mid-Range Resistance Measurements (100mΩ to 1MΩ)

- Option 1
  - 1 Model 4200-Semiconductor Characterization System with 4 Source-Measure Units
    - Includes turn-key software for electrical resistivity measurement
- Option 2
  - 1 Model 6220 Precision Current Source
  - 1 Model 2700 DMM
  - 1 Model 7709 6x8 Matrix Switch Card
    - Can do 2 samples at a time

Mid-Range Resistance Measurements (100mΩ to 1MΩ) (cont'd)

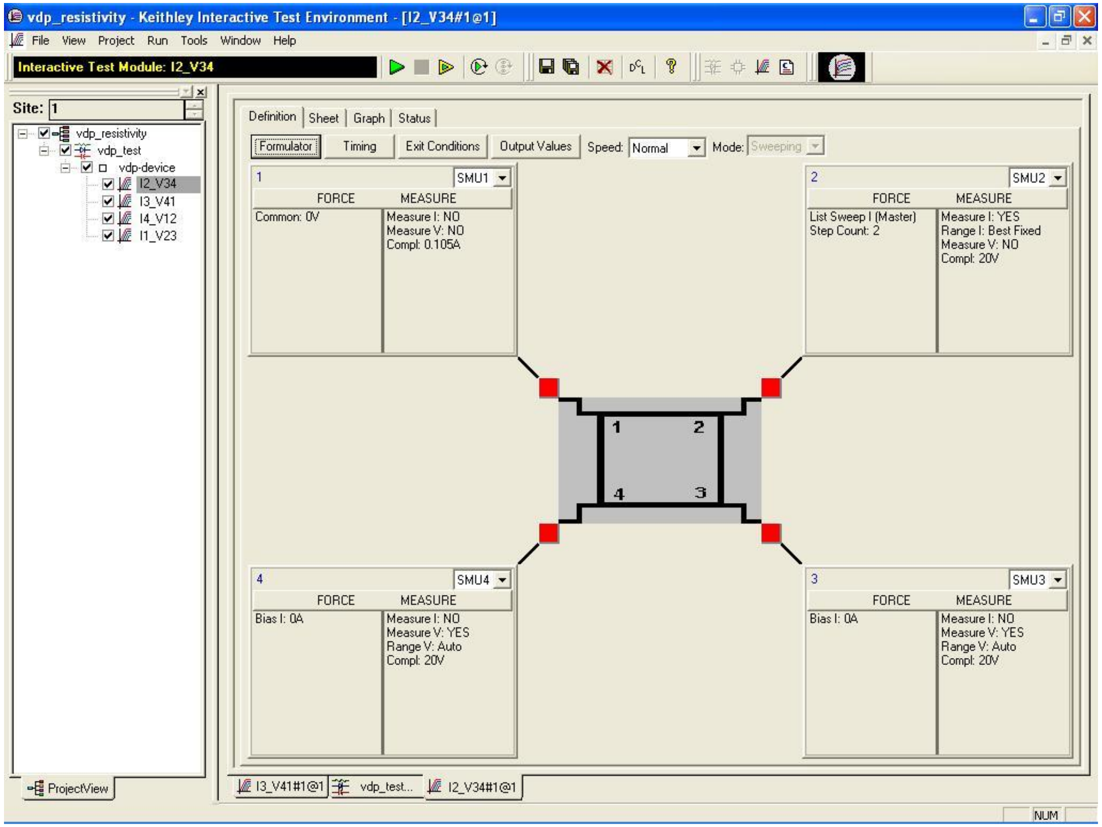
- Option 1: 4200-SCS with
  4 Source-Measure Units (SMUs)
  - 4200 includes project to measure van der Pauw resistivity
  - Project changes functions of SMU to be either current source or voltmeter
    - This eliminates the need for a switch matrix





Mid-Range Resistance Measurements (100mΩ to 1MΩ) (cont'd)

- **Option 1: 4200-SCS with 4 SMUs**
  - Resistivity derived by taking eight current-voltage measurements around periphery of sample
  - The 4200 can also be used to make I-V and C-V measurements on devices



vdp_resistivity - Keithley Interactive Test Environment - [I2_V34#1@1]

Interactive Test Module: I2_V34

Site: 1

- ☑ vdp_resistivity
  - ☑ vdp_test
    - ☑ vdp-device
      - ☑ I2_V34
      - ☑ I3_V41
      - ☑ I4_V12
      - ☑ I1_V23

Speed: Normal

Mode: Sweeping

1	SMU1
FORCE	MEASURE
Common: 0V	Measure I: NO Measure V: NO Compl: 0.105A

2	SMU2
FORCE	MEASURE
List Sweep I (Master) Step Count: 2	Measure I: YES Range I: Best Fixed Measure V: NO Compl: 20V

4	SMU4
FORCE	MEASURE
Bias I: 0A	Measure I: NO Measure V: YES Range V: Auto Compl: 20V

3	SMU3
FORCE	MEASURE
Bias I: 0A	Measure I: NO Measure V: YES Range V: Auto Compl: 20V

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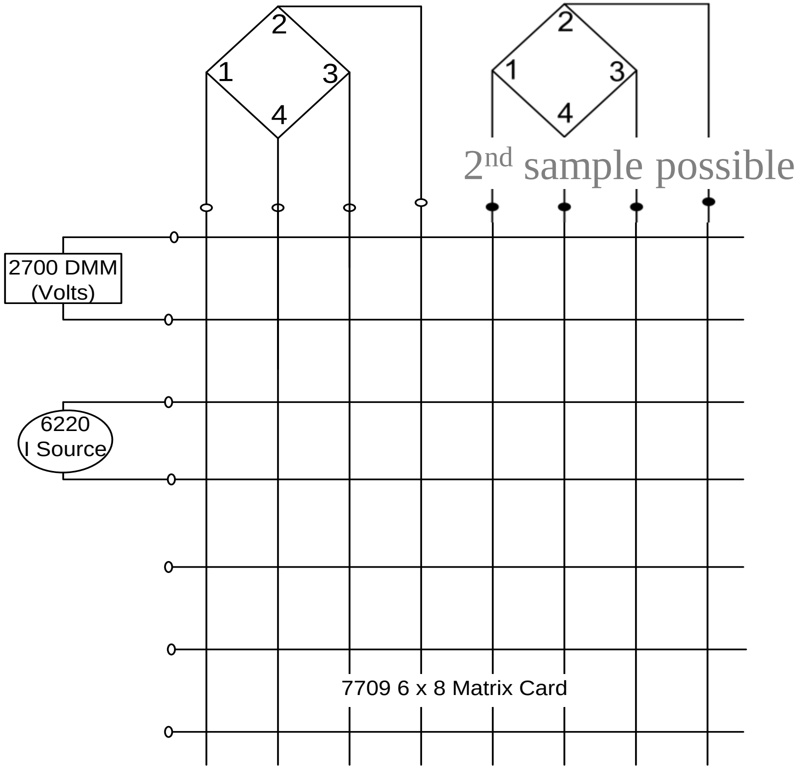
Mid-Range Resistance Measurements (100mΩ to 1MΩ) (cont'd)

- **Option 2 connection scheme**
  - **6220 Current Source, 2700 DMM, 7709 Matrix Card**

DMM + Switch Module

Current Source



Hall Effect Measurement Equipment

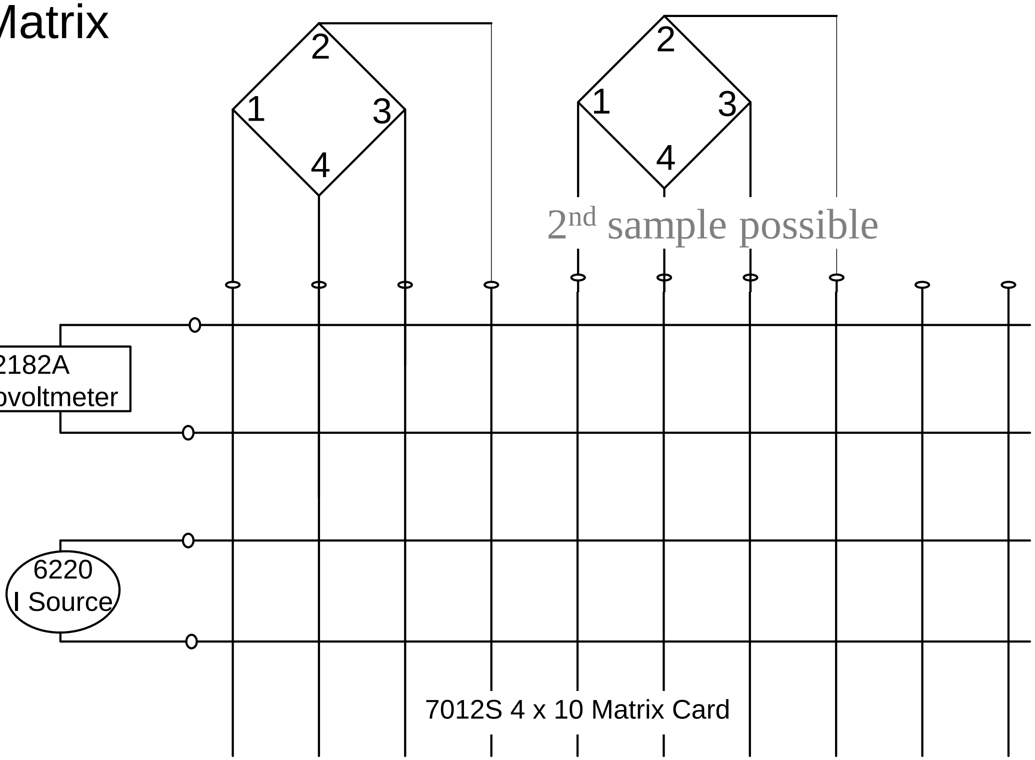
- Mid-range resistance
- Low resistance
  - 1 μΩ to 1 MΩ
    - Typically metals, highly doped Si or Ge (>10^{17} cm^{-3}); SiGe; superconductors; GMR/TMR
  - Challenge here is that the low-resistance sample results in very low measured V
    - Need nV measurements
    - Force higher currents to allow higher measured voltage
- Low-to-high (wide range) resistance
- Mid- to super-high resistance

Low Resistance Measurements (1µΩ to 1MΩ)

- Connection scheme
  - 6220 Current Source, 2182A Nanovoltmeter, 7001/7012S 4x10 Switch Matrix

Nanovoltmeter

Current Source



Switch Mainframe

Techniques for Eliminating Errors when Making Low Voltage Measurements

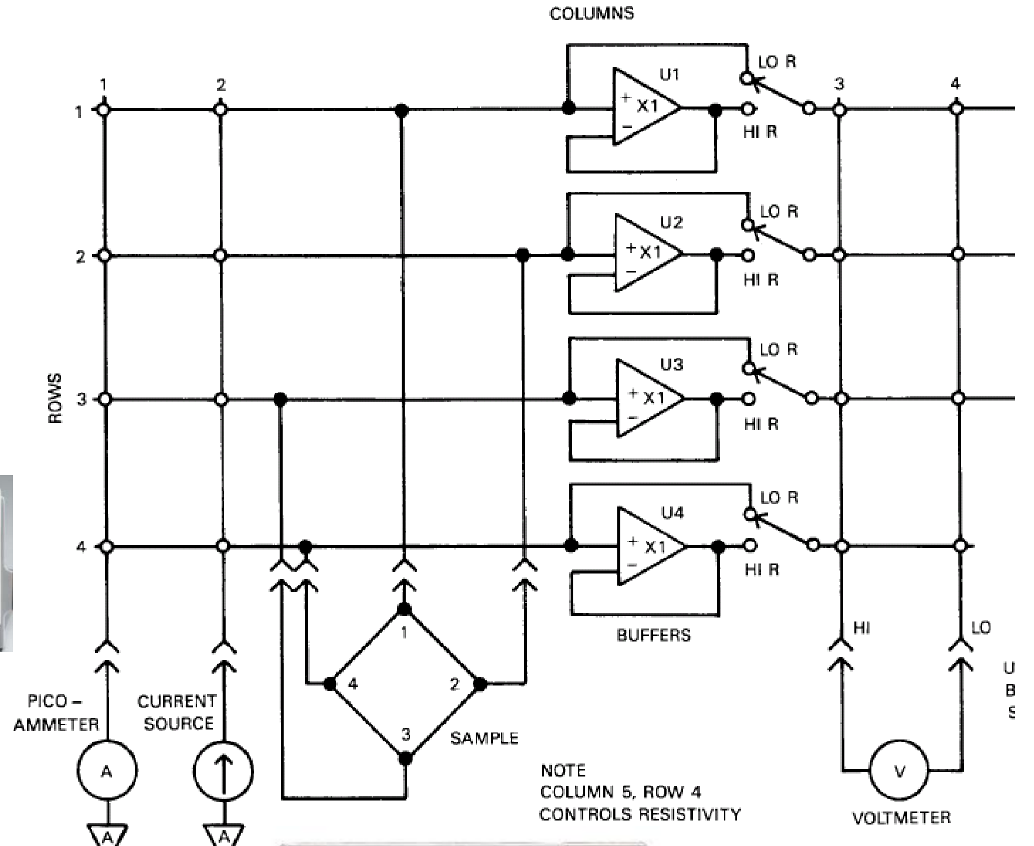
- Minimize sources of thermoelectric voltages
  - Whenever possible use the same materials in all connections
  - Use all copper connections and copper wire
  - Reverse current source polarity and average readings
- Allow test equipment to warm up and reach thermal equilibrium
- Minimize temperature gradients across the sample
- Eliminate ground loops
- Shield the system

Hall Effect Measurement Equipment

- Mid-range resistance
- Low resistance
- ☞ **Low-to-high (wide range) resistance**
  - 1µΩ to 1TΩ
    - Typically thin film photovoltaics like CIGS, CdTe, HgCdTe, increasingly doped material
- Mid- to super-high resistance

Wide-Range Resistance Measurements (1µΩ to 1TΩ) Instrument Setup (cont'd)

Model 7065 Hall Effect Card Based System Configuration:



Switch Mainframe

Picoammeter

6220

Current Source

2182A

Nanovoltmeter

Hall Effect Measurement Equipment

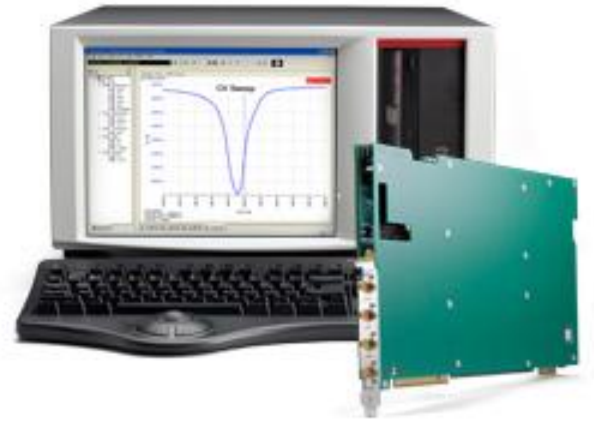
- Mid-range resistance
- Low resistance
- Low-to-high (wide range) resistance
- **Mid- to super-high resistance**
  - **100mΩ to 10TΩ**
    - **Typically GaAs, GaN, InP, InGaAs, AlGaAs, SiC, semi-insulating Si or CdTe**
  - **Adds 1 more decade of high resistance compared to "Low-to-high resistance" configuration**

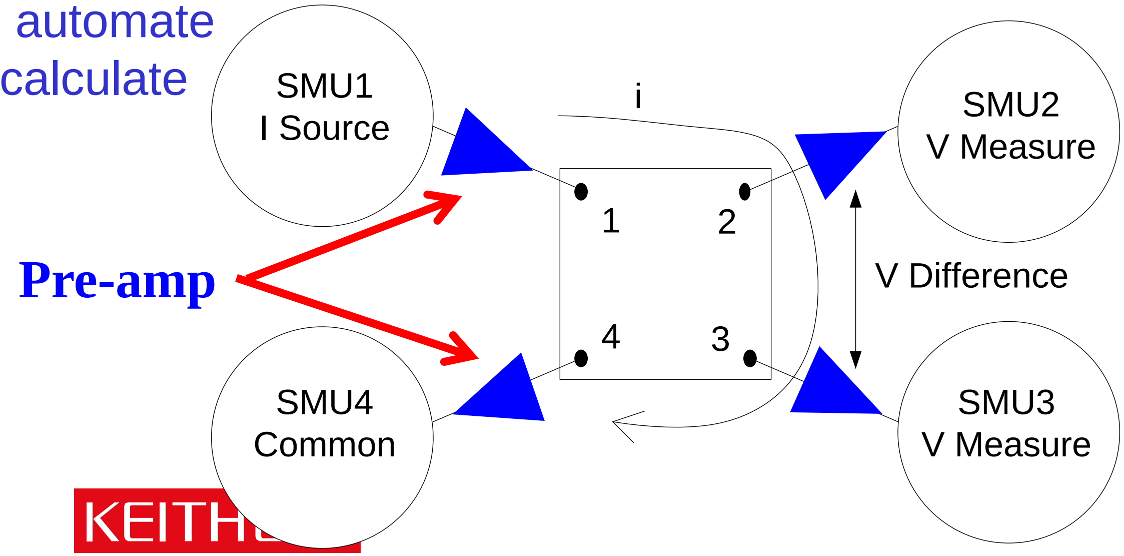
Mid- to Super-High Resistance Measurements (100 mΩ to 10 TΩ)

- Option 1
  - 1 Model 4200-Semiconductor Characterization System with 4 Source-Measure Units (SMUs) and 4 preamps
    - Includes turn-key software for electrical resistivity
- Option 2
  - 1 Model 6220 Precision Current Source
  - 2 Model 6514 Electrometers
  - 1 Model 2000 DMM
  - 1 Model 7001 Switch Mainframe
  - 1 Model 7152 Low Current 4x5 Matrix Switch Card
- Option 3:
  - Use 2 x 2636A SourceMeter® Instruments

Mid- to Super-High Resistance Measurements (100mΩ to 10TΩ)

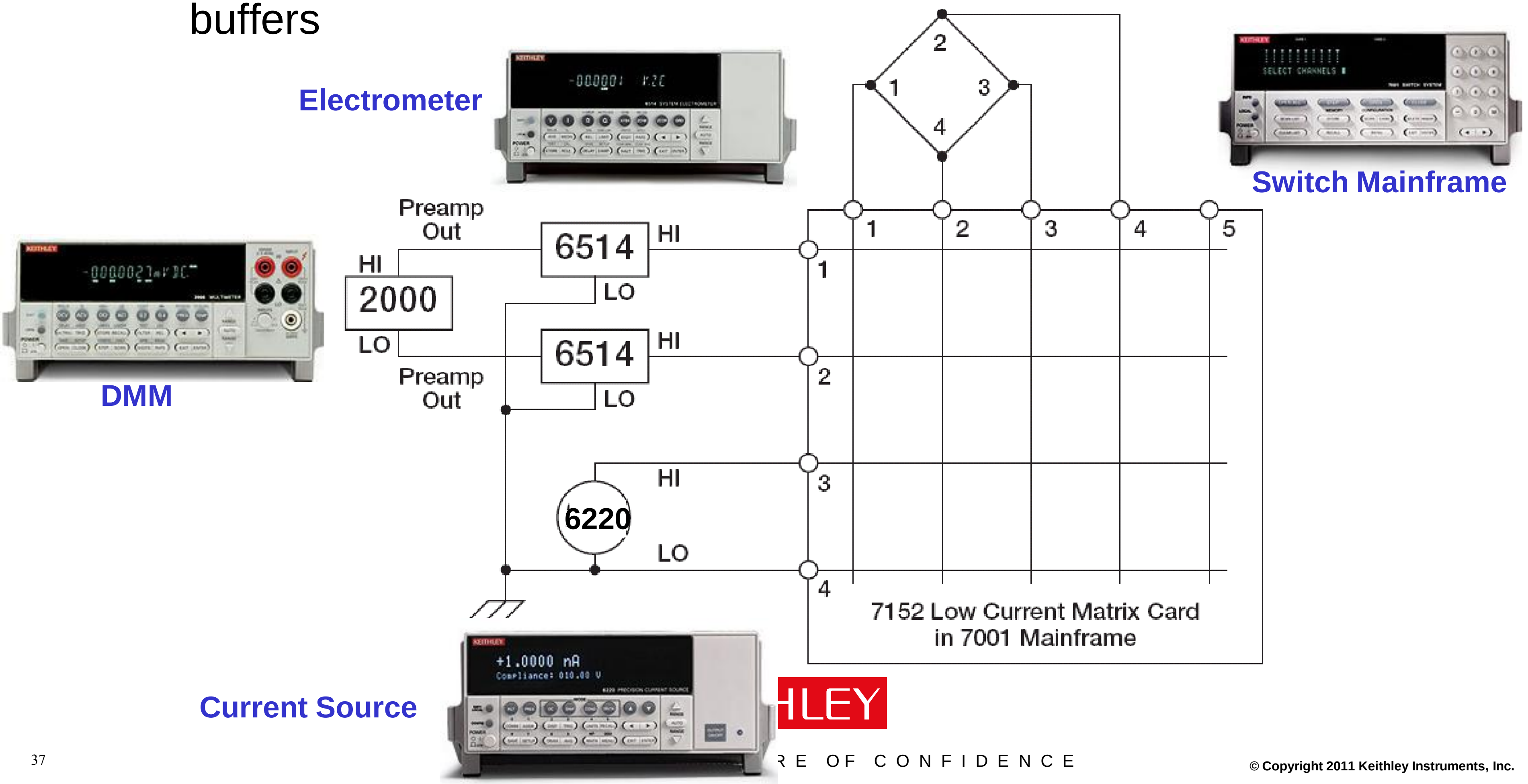
- Option 1: Model 4200-SCS with 4 SMUs and 4 pre-amps
  - Input impedance >10^{16} Ω
  - Accurate low current sourcing, pA
  - No leakage errors due to mechanical switches
  - Includes software to automate measurements and calculate resistivity





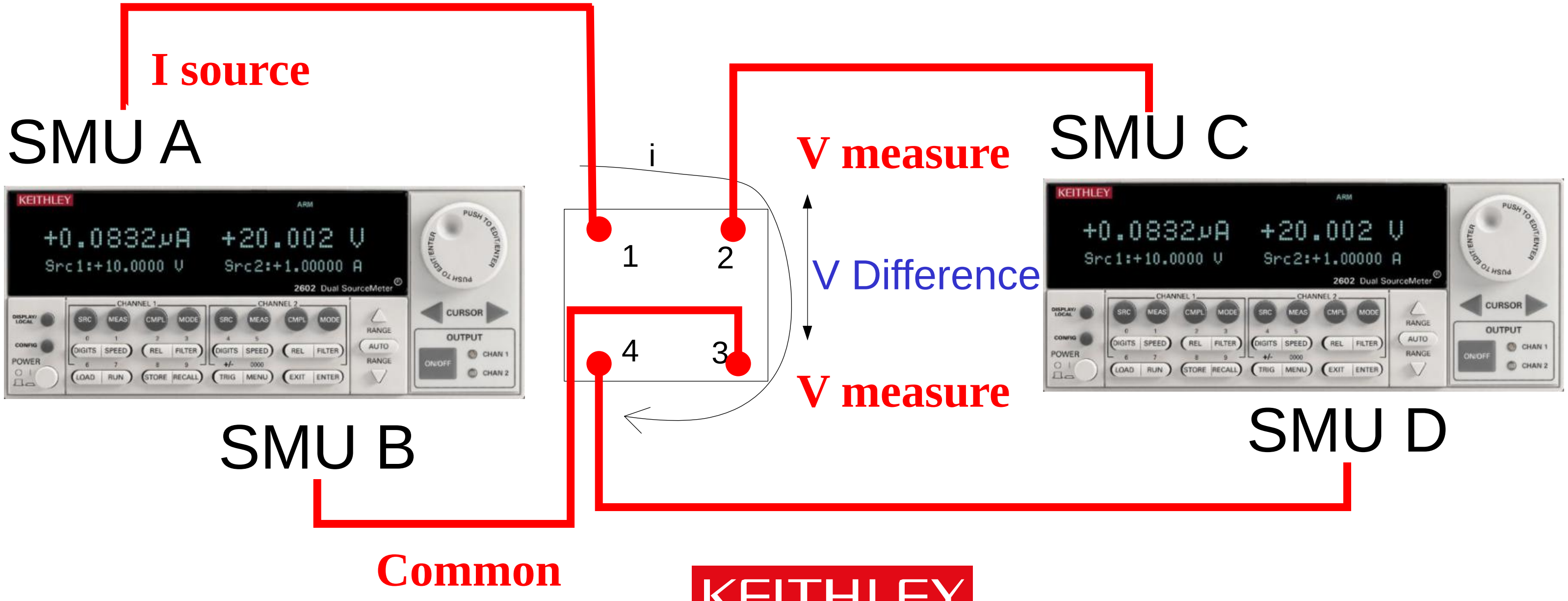
Mid- to super-high resistance measurements (100 mΩ to 10 TΩ): Other options

- Option 2: Model 6514 Electrometers used as high impedance buffers



Mid- to Super-High Resistance Measurements (100 mΩ to 10 TΩ): Other Options

- **Option 3: Use 2 x 2636As SourceMeter Instruments**
  - Adds I-V sweep capability
  - Software options: ACS-Basic, TSP® Express, downloaded embedded tests scripts, or custom software (Services)
  - No switch needed

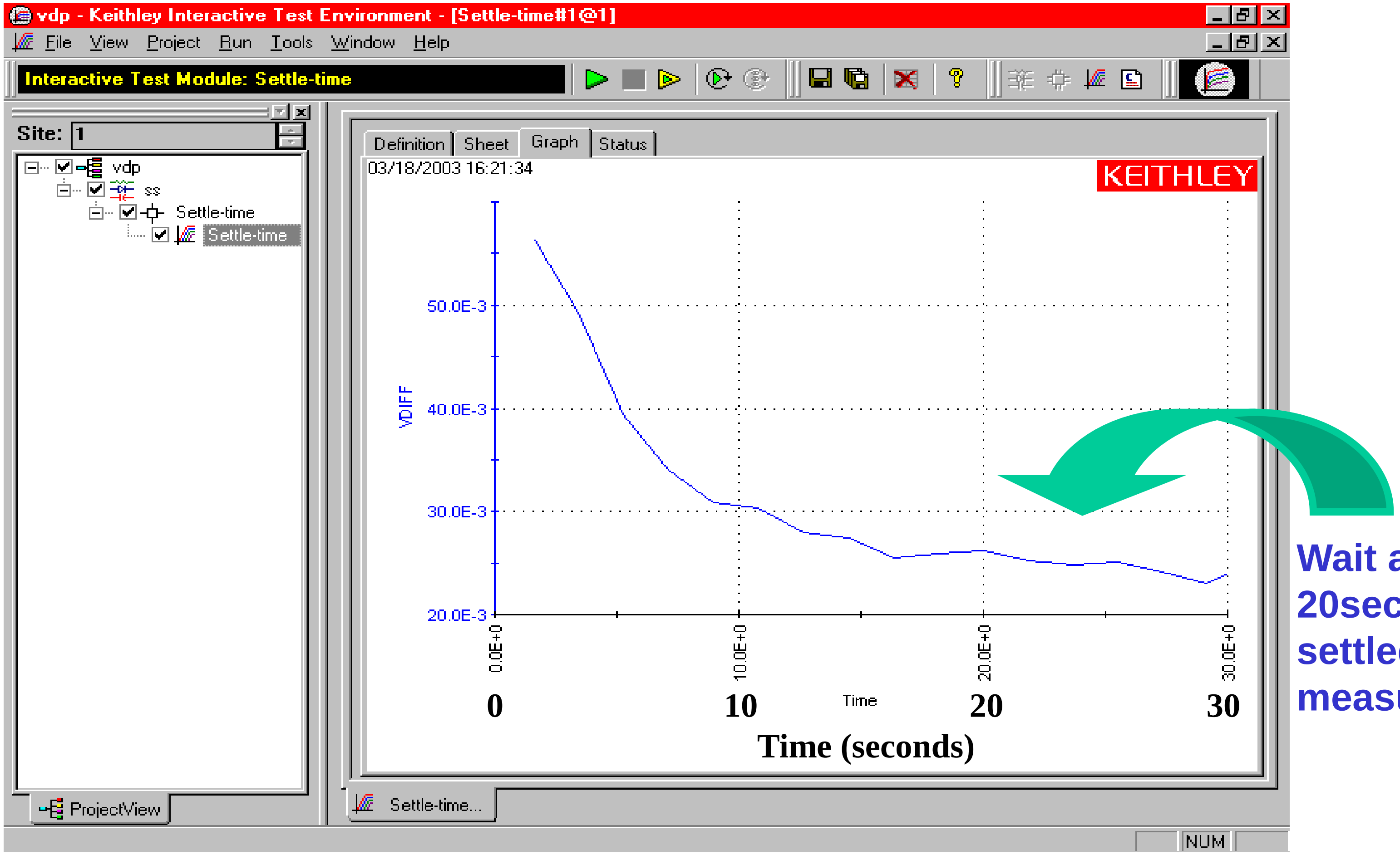


Making Good Measurements on High Resistivity Materials

- Electrostatic shielding to minimize electrical interference
  - Shield the DUT and all sensitive circuitry
  - Use shielded cabling
  - Connect the shield to the low terminal of the system

- Use guarding to reduce the effects of leakage current in system
  - Guarded current source
  - Guarded voltmeters
  - Use triax cable instead of coax cable
- Allow sufficient settling time
  - Source I and measure V as a function of time to determine appropriate settling
  - A diamond sample can take 10 – 15 minutes for settling

Settling Time of a $10^{12}\Omega$ Resistance Sample



Wait at least 20sec for a settled measurement

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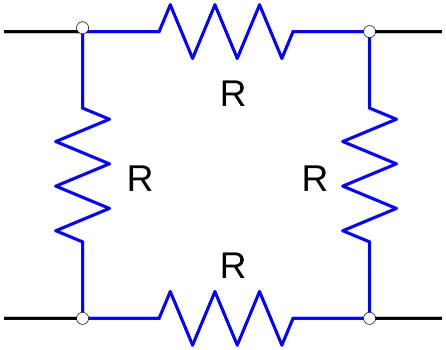
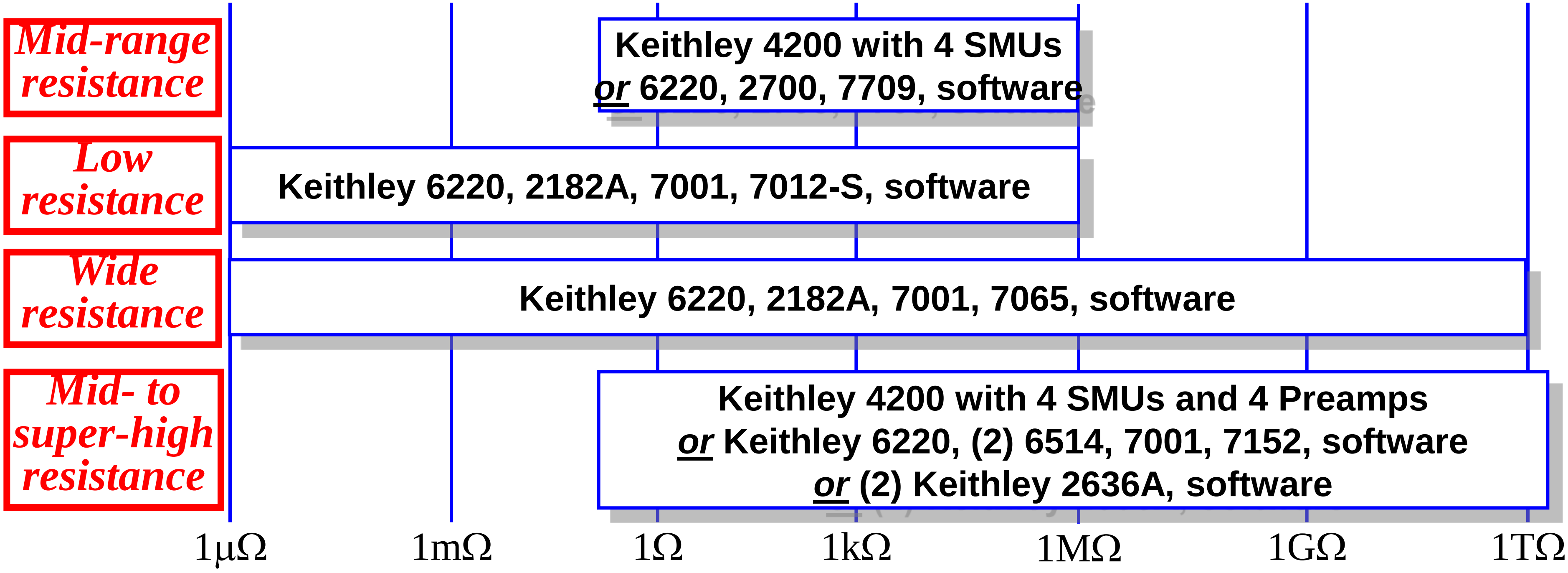
Building Confidence in Your System

- Build a test structure using four resistors of equal value that are similar in magnitude to the resistance of the sample under test
- Have a known good sample characterized by a recognized laboratory



Overview of Keithley Offerings



Mid-range resistance

Keithley 4200 with 4 SMUs
or **6220, 2700, 7709, software**

Low resistance

Keithley 6220, 2182A, 7001, 7012-S, software

Wide resistance

Keithley 6220, 2182A, 7001, 7065, software

Mid- to super-high resistance

Keithley 4200 with 4 SMUs and 4 Preamps
or **Keithley 6220, (2) 6514, 7001, 7152, software**
or **(2) Keithley 2636A, software**

Sample Resistance (Ω)

(actual selection depends on Total Resistance = Sample Resistance + Contact Resistance)

Sample Resistance ≈ ρ/t

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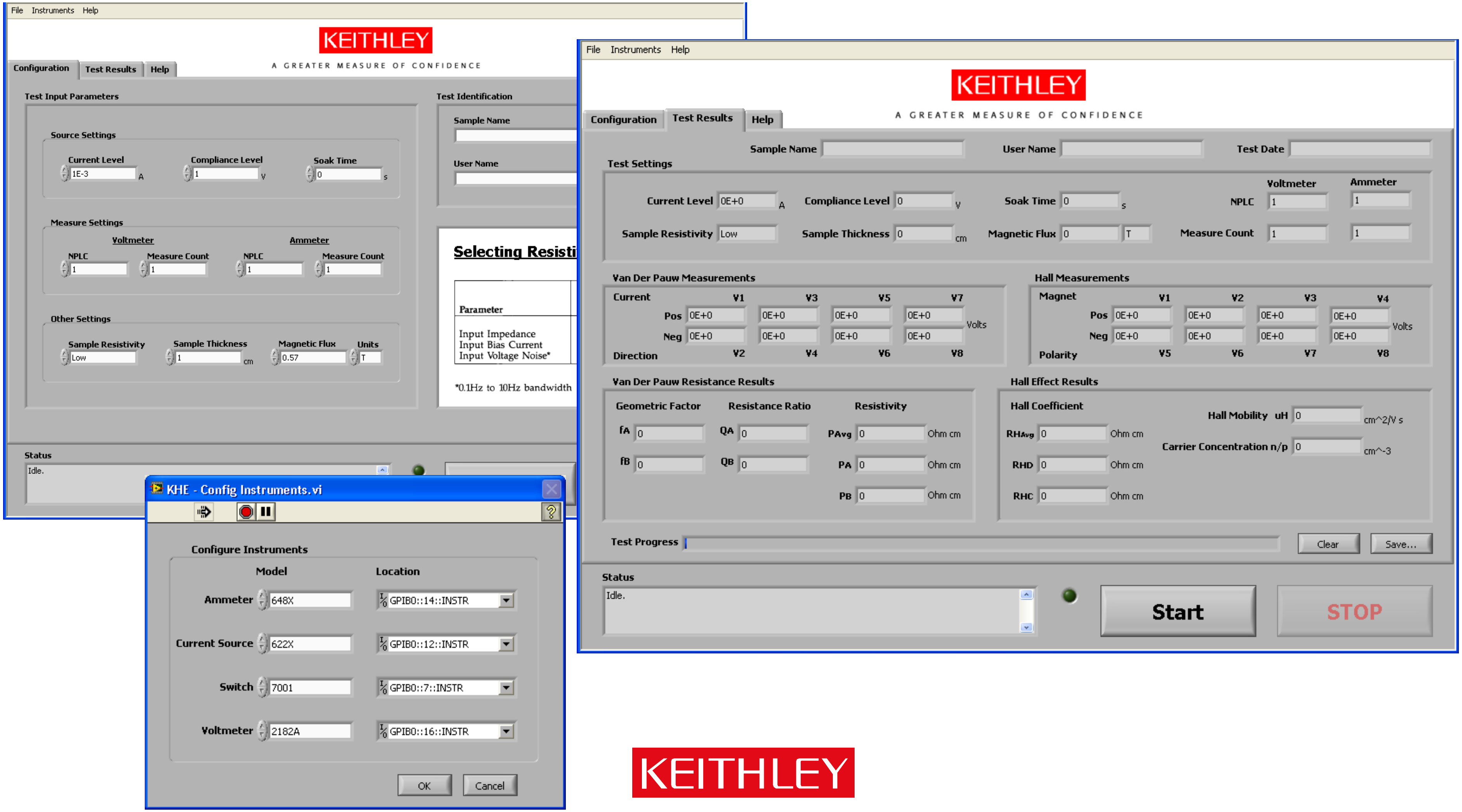
Example Custom GUI from Keithley Software Services



Test Input Parameters

Source Settings
Current Level: 1E-3 A
Compliance Level: 1 V
Soak Time: 0 s

Measure Settings
Voltmeter NPLC: 1
Voltmeter Measure Count: 1
Ammeter NPLC: 1
Ammeter Measure Count: 1

Other Settings
Sample Resistivity: Low
Sample Thickness: 1 cm
Magnetic Flux: 0.57
Units: T

Test Identification
Sample Name:
User Name:

Selecting Resisti

Parameter
Input Impedance Input Bias Current Input Voltage Noise*

*0.1Hz to 10Hz bandwidth

Status: Idle.

Configure Instruments

	Model	Location
Ammeter	648X	GPIB0::14::INSTR
Current Source	622X	GPIB0::12::INSTR
Switch	7001	GPIB0::7::INSTR
Voltmeter	2182A	GPIB0::16::INSTR

Test Results

Sample Name:
User Name:
Test Date:

Test Settings
Current Level: 0E+0 A
Compliance Level: 0 V
Soak Time: 0 s
Sample Resistivity: Low
Sample Thickness: 0 cm
Magnetic Flux: 0 T

	Voltmeter	Ammeter
NPLC	1	1
Measure Count	1	1

Van Der Pauw Measurements

Current	V1	V3	V5	V7
Pos	0E+0	0E+0	0E+0	0E+0
Neg	0E+0	0E+0	0E+0	0E+0
Direction	V2	V4	V6	V8

Volts

Hall Measurements

Magnet	V1	V2	V3	V4
Pos	0E+0	0E+0	0E+0	0E+0
Neg	0E+0	0E+0	0E+0	0E+0
Polarity	V5	V6	V7	V8

Volts

Van Der Pauw Resistance Results
Geometric Factor: fA 0, fB 0
Resistance Ratio: QA 0, QB 0
Resistivity: PAvg 0 Ohm cm, PA 0 Ohm cm, PB 0 Ohm cm

Hall Effect Results
Hall Coefficient: RHAvg 0 Ohm cm, RHD 0 Ohm cm, RHC 0 Ohm cm
Hall Mobility uH: 0 cm^2/V s
Carrier Concentration n/p: 0 cm^-3

Test Progress

Status: Idle.

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A GREATER MEASURE OF CONFIDENCE

Additional Reference Material

- Application Note: Four-Probe Resistivity and Hall Effect Measurements with the Model 4200-SCS
  - http://www.keithley.com/support/data?asset=15222

- Low Level Measurements Handbook, Section 4.4

- Semiconductor Material and Device Characterization by Deiter Schroder

- 6220 Current Source Datasheet: http://www.keithley.com/support/data?asset=15911
- 2182A Nanovoltmeter: http://www.keithley.com/support/data?asset=15912
- 6514 Electrometer: http://www.keithley.com/support/data?asset=387
- 2000 DMM: http://www.keithley.com/support/data?asset=359
- 7001 Switch Mainframe: http://www.keithley.com/support/data?asset=390
- 7012-C 4x10 Matrix Card: http://www.keithley.com/support/data?asset=393
- 7152 Low Current Matrix Card: http://www.keithley.com/support/data?asset=426
- 7065 Hall Effect Switch Card: http://www.keithley.com/support/data?asset=560

Contact Keithley with Your Questions

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