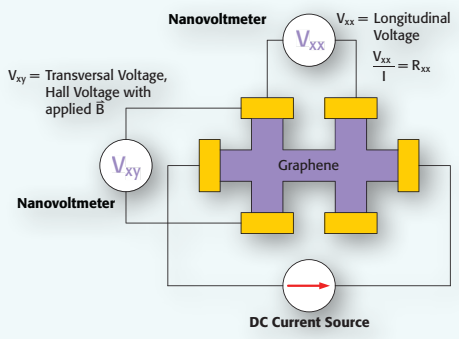
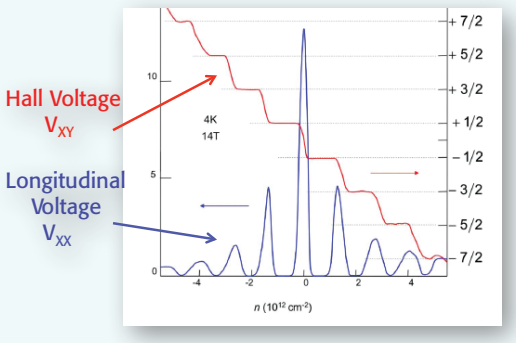
MEASUREMENT TECHNIQUES FOR CHARACTERIZING GRAPHENE, CARBON NANOTUBES, AND NANO-MATERIALS AND DEVICES

LOW POWER, LOW VOLTAGE, LOW RESISTANCE

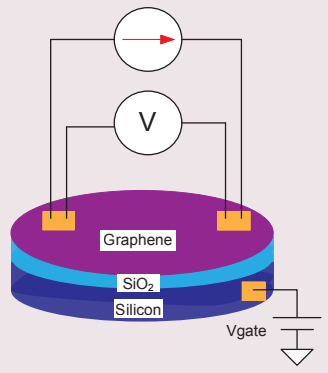
Measurement Technique for Hall Voltage and Resistivity Measurements



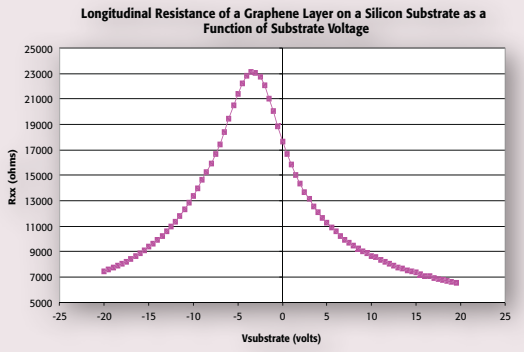
Quantum Hall Effect Measurements on Graphene



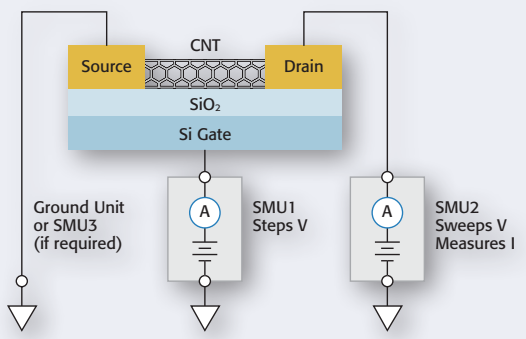
Technique for Measuring Resistance as a Function of Gate Voltage



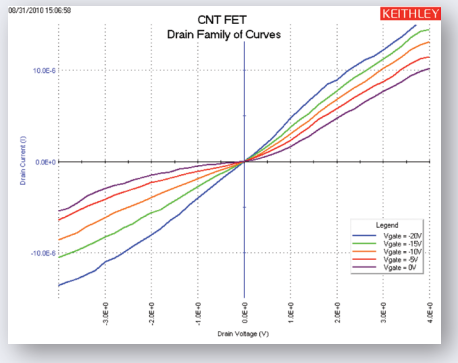
Resistance vs. Gate Voltage of Graphene Device



Circuit to Measure Drain Family of Curves on a Carbon Nanotube



Current vs. Voltage Characteristics of Carbon Nanotube FET

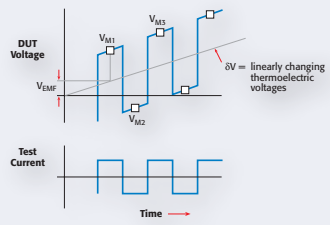


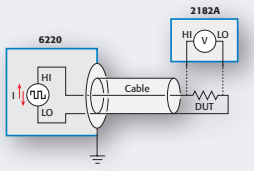
Avoiding Sources of Error When Measuring Low Power Materials and Devices

Noise: External Noise Sources • Low Frequency Noise • Johnson Noise

Use the Delta Mode Method to Eliminate Voltage Offsets and Noise

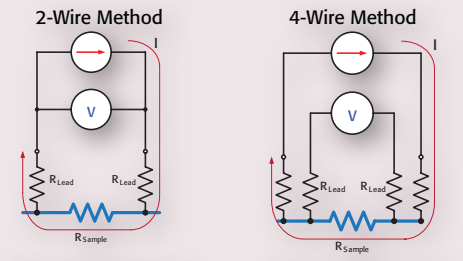
The Delta method consists of alternating the current source polarity and using a moving average of voltage readings to calculate the resistance. Averaging reduces the noise bandwidth and therefore





- **External Noise Sources = interferences created by motors, computer screens, or other electrical equipment**
- **Control these External Noise Sources by:**
  - Shielding and filtering.
  - Remove or turn-off the noise source.
  - When using DC instruments, integrate each measurement for an integer number of power line cycles. The line cycle noise will "average out" when the integration time is equal to an integration number of power line cycles.

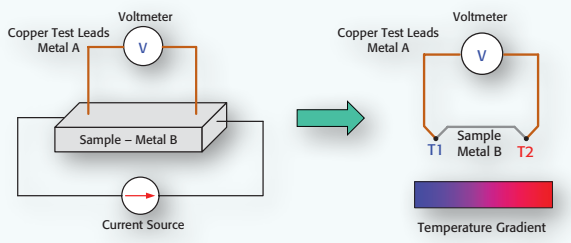
Test Lead Resistance: Eliminate Lead Resistance by Using the 4-Wire Method



Measured Resistance: $V_M/I = R_{Sample} + 2R_{Lead}$

Measured Resistance: $V_M/I = R_{Sample}$

Eliminate Thermoelectric Voltage Effects

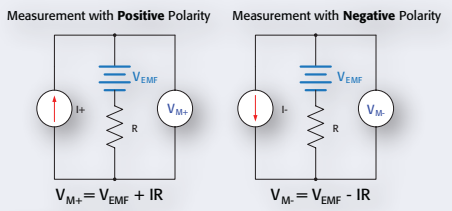


Thermoelectric voltages are generated when dissimilar metals (Metal A and Metal B) in the circuit are at different temperatures (T1 and T2).

Ways to Reduce Thermoelectric Voltages

- Construct test circuits using the same materials for interconnects.
- Minimize temperature gradients within the test circuit.
- Allow the test equipment to warm up.
- Use an offset compensation method.

Use the Current Reversal Method to Eliminate Voltage Offsets (V_{EMF})



$V_{M+} = V_{EMF} + IR$

$V_{M-} = V_{EMF} - IR$

Voltage Measurement:

$$V_M = \frac{V_{M+} - V_{M-}}{2} = \frac{V_{EMF} + IR - (V_{EMF} - IR)}{2} = IR$$

Use Instrumentation with Sufficient Sensitivity

Use a Nanovoltmeter to Measure Voltage Drops

- When measuring the resistances of conductors or other low power materials, very small voltages are measured, typically in the **microvolt** and **nanovolt** range.
- To measure these very small voltage drops, use a sensitive voltmeter such as a nanovoltmeter.
- Verify the product specifications to make sure the measurement resolution and accuracy are sufficient to perform the sensitive measurement part of your application.

Channel 1 Range		Resolution	Input Resistance	Accuracy: ±(ppm of reading + ppm of range) (ppm = parts per million) (e.g. 10ppm = 0.001%) 24 Hour[1] T_{CAL} ±1°C	90 Day T_{CAL} ±5°C	1 Year T_{CAL} ±5°C	2 Year T_{CAL} ±5°C
10.000000	mV[2,3,4]	1 nV	>10 GΩ	20 + 4	40 + 4	50 + 4	60 + 4
100.00000	mV	10 nV	>10 GΩ	10 + 3	25 + 3	30 + 4	40 + 5
1.0000000	V	100 nV	>10 GΩ	7 + 2	18 + 2	25 + 2	32 + 3
10.000000	V	1 μV	>10 GΩ	2 + 1[5]	18 + 2	25 + 2	32 + 3
100.00000	V[4]	10 μV	10 MΩ ±1%	10 + 3	25 + 3	35 + 4	52 + 5

Use Appropriate Current Source

- Current source should be bipolar to perform current reversals to eliminate voltage offsets and reduce noise.
- Current source should be capable of accurately sourcing very low currents (<1E-6A) for low level test devices and materials.
- The current source should have an adjustable voltage compliance to limit voltage to a safe level to avoid damage to the device.
- The current source should have constant output so user knows the exact value forced to the material – unlike using a voltage source and a resistor.

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