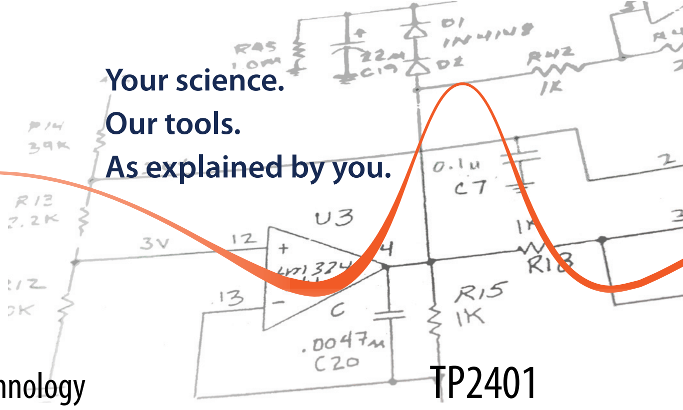

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Four-Point AC Resistance Measurements

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TP2401

August 15, 2024

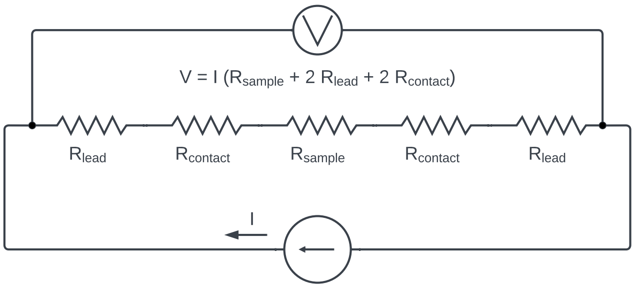
ABSTRACT

Electrical resistivity is a fundamental material property, critical for understanding electronic behavior in conductors, semiconductors, superconductors, and more. The simplest electrical resistance measurement—a two-terminal DC measurement of voltage due to an applied current—can be contaminated by low-frequency noise, lead and contact resistance, and thermal offsets. Here we present the four-terminal AC resistance measurement as a solution to these issues, in the context of understanding the flat electronic bands and superconductivity of $CaNi_2$ and $Ca(Rh_{0.98}Ru_{0.02})_2$. We describe sample preparation, the measurement setup, acquisition and analysis of data, as well as troubleshooting of common issues.

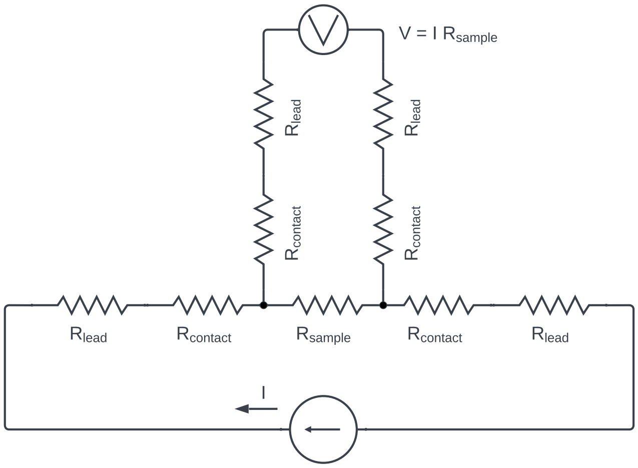
Introduction

This technique paper describes one of the most common uses for a lock-in amplifier—the four-point AC resistance measurement (also known as four-terminal or four-wire). The resistance (or resistivity, when normalizing by the sample geometry) of a material or device is a fundamental property, useful for understanding a material's electronic behavior whether from the perspective of physics, materials science, or electrical engineering [1–3]. Indeed, it is one of the first measurements conducted in our group to understand a newly synthesized conductive material. For example, a metal's resistivity will decrease with decreasing temperature, while a semiconductor or insulator's resistivity will increase as charge carriers "freeze out." To further quantify the quality of a metal, the effect of impurities and crystal defects can be isolated by measuring the ratio of resistance at room temperature divided by the resistance at low temperature ($\lesssim$4 K). This is the so-called residual resistivity ratio, or RRR. A perfect metallic crystal would have zero resistance at zero temperature (infinite RRR), while impurities cause the resistance to saturate to a finite value (smaller RRR). Longitudinal resistance is of course the key measurement for identifying superconductivity [4, 5]. Other uses of resistivity measurements include identification of topological band features, which can have a profound impact on longitudinal and Hall conductivity [6–8], and Fermi surface characterization via quantum oscillations of the resistivity in high magnetic fields (Shubnikov–de Haas oscillations) [4, 5, 9].

There are two main advantages to the four-point AC resistance technique over simpler methods. First, the four-point geometry removes the effects of contact resistance, allowing a measurement of the intrinsic device resistance. This is shown schematically by comparing two-point and four-point measurements in Fig. 1.



(a) Two-point resistance measurement, showing contributions from contacts and leads to the voltage measurement.



(b) Four-point resistance measurement. For a high impedance voltmeter, the contact and lead resistances can be neglected.

Figure 1: Comparison of two-point and four-point resistance measurements.

Second, the measurement of an AC voltage at the frequency of the AC excitation current allows one to employ a lock-in measurement, which provides narrow bandwidth extraction of potentially small signals (at the frequency of interest) in the presence of large noise [10]. Measurement at AC also provides isolation from thermoelectric voltages present in DC measurements. Once you understand lock-in detection in the context of longitudinal resistivity, the principle can be easily extended to other applications where an AC voltage is measured as a response to an AC excitation such as Hall measurements, thermometry, gated devices, torque magnetometry, AC susceptibility measurements, and more.

Experimental Setup and Measurement Protocol

Equipment and Materials

To follow along with the measurements presented in this **Technique Paper**, you will need the following:

- Stanford Research Systems **SR860 Lock-In Amplifier** (or similar)
- Stanford Research Systems **CS580 Voltage Controlled Current Source** (or similar AC current source)
- Coaxial or twisted pair cables to connect to the device under test (DUT)
- A four-contact sample
- A sample environment that provides control of some external or device parameter such as temperature, magnetic field, electric field, pressure, or gate voltage.

Device Geometry

An idealized device is depicted in Fig. 2. The sample or device under test (DUT) is patterned or polished into the desired shape. Alternating current is applied between the I+ and I- contacts, and the voltage is measured across the V+ and V- contacts. The use of separate current and voltage leads (along with a high impedance voltmeter) eliminates the effect of lead resistance from the voltage measurement. Though outside the scope of this report, it is worth noting that other contact geometries can be used such as Hall [1], van der Pauw [10], Montgomery [11], and Corbino disk [12]. These each have specific use cases, or various benefits and drawbacks compared to the straightforward 4-point contact geometry shown in Fig. 2.

To make good electrical contacts in our lab, we use 25 μm to 50 μm thick gold wire and DuPont silver paint 4922N or EpoTek H20E applied with a fine wire or eyebrow hair. Lithographically-defined contacts may be used for fabricated devices. Making good contacts is an art in and of itself, and can only be learned through trial and error—in particular, learning the correct dilution of solvent in silver paint and a method to apply the silver paint to the wire is critical. Too much solvent and the paint will run across the crystal, but too little and the paint will just stick to the gold wire without forming a good electrical bond between the wire and the sample. Further, if the bond between the paint and the sample is not robust, the contact may shift or even break off entirely when the sample is cooled (identifiable as discontinuities in measured voltage). Though the contact resistance does not directly affect the measured value in a 4-point resistance measurement, it can still introduce additional noise and ohmic heating to your measurement, so it is best to minimize the contact resistance. Contact resistance can be estimated with a two-point resistance measurement across two contacts at a time using a handheld multimeter, or with greater care if electrostatic discharge is a concern. With silver paint contacts, contact resistance under 10 Ω is ideal.

Theory

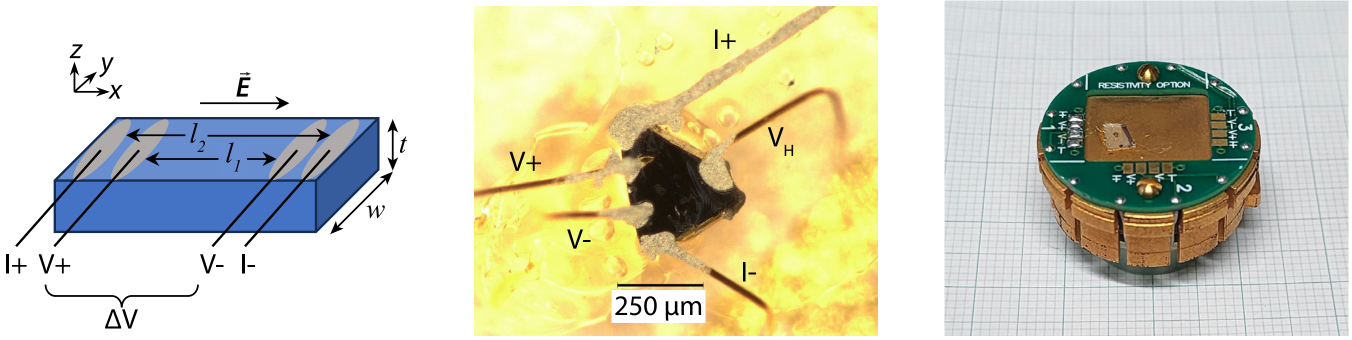
We assume that the current density $\mathbf{j}$ flows uniformly throughout the cross-sectional area $A = w \times t$ of the sample. In layered or highly anisotropic materials where the resistivity along the z-axis is much larger than that in the xy-plane, the contacts should extend along the side of the sample to short the layers together. Under these assumptions, the electric field $\mathbf{E}$ is uniform inside the sample, leading to equipotential surfaces that lie perpendicular to the current flow. Therefore, the electric field in the sample is $E = \Delta V / l_1$. Using Ohm's law $\rho = \mathbf{E}/\mathbf{j}$ for a current density $j = I/A$, we can write the resistivity as

$$\rho = \frac{\Delta V A}{I l_1} \tag{1}$$

In a resistivity measurement, I is applied (and known), while ΔV is the measured quantity. Let's rearrange Eq. (1) to estimate the measured voltage:

$$\Delta V = \frac{\rho l_1}{A} I \tag{2}$$

For a typical metallic sample with $\rho = 1 \times 10^{-8}\,\Omega\,\mathrm{m}$, $l_1 = 1\,\mathrm{mm}$, $A = 10\,\mu\mathrm{m} \times 100\,\mu\mathrm{m}$, and $I = 1\,\mathrm{mA}$, we get $\Delta V = 10\,\mu\mathrm{V}$, which is quite small, but measurable. We therefore see that to maximize the measured signal ΔV, we should increase the current or the device length, or decrease the cross-sectional area. In a Hall measurement, it is also desirable to minimize the sample thickness t and maximize the sample width w. Resistivity has SI units of



(a) Schematic of four-point resistance measurement geometry with current terminals I+ and I- (separated by distance l_2), voltage terminals V+ and V- (separated by l_1), and cross-sectional area $A = w \times t$. Sample shown in blue, contacts in silver, wires in black.

(b) Optical microscope image of a hand-wired single crystal of $Ca(Rh_{0.98}Ru_{0.02})_2$ with additional V_H lead for Hall resistance measurement. Black 250 µm bar included for scale [9] .

(c) A sample puck to be loaded into cryostat for measurement, shown on 1 mm grid paper.

Figure 2

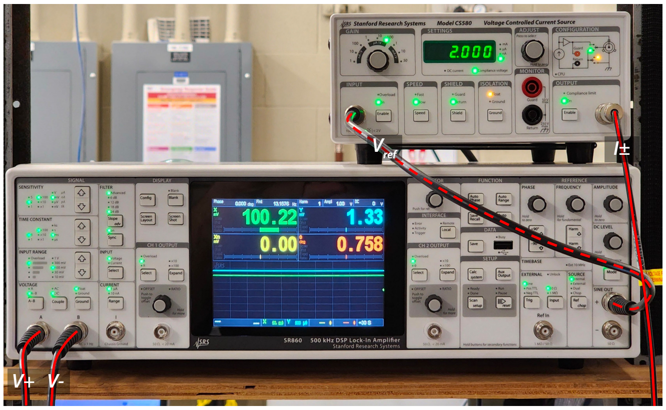
Ω m, but since many conducting materials have resistivity of order 1×10^{-8} Ω m, you will often find resistivity expressed in units of µΩ cm. In cases where the contact geometry deviates from the ideal, the absolute resistivity may be incorrectly calibrated by some factor of order unity. In general, $\mathbf{E}$ and $\mathbf{j}$ are vectors, and ρ is a tensor: $E_i = \rho_{ij} j_j$. This is useful when the sample is anisotropic or magnetic field is applied creating off-diagonal Hall conductivity/resistivity. The quantity in Eq. (1) is therefore more properly written as ρ_{xx} (following the geometry in Fig. 2a, with I_x applied and ΔV_x measured).

Setting Up the Instruments

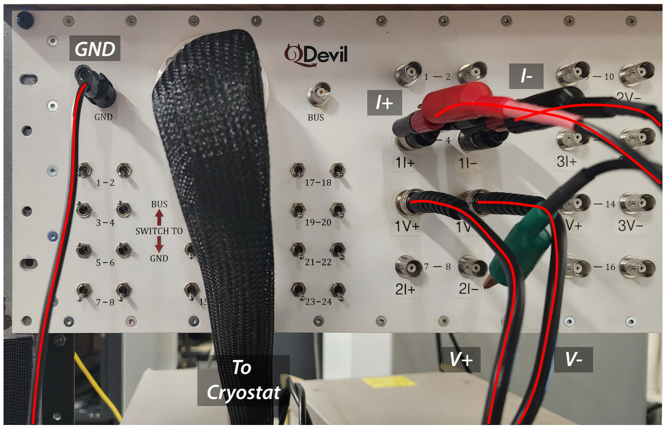
First, connect a BNC coaxial cable from the Sine Out of the SR860 lock-in to the Input of the CS580 (see Fig. 3a). Next, connect the center and inner shield of the triaxial output cable of the CS580 (red and black alligator clips, respectively) to the I+ and I− terminals of your device. Finally, connect the V+ and V- terminals from your device to the lock-in voltage Inputs A and B, respectively. *It is safest to make or break connections to your device only when the excitation current is disabled!* Otherwise, large voltage spikes can be sent to your device, potentially leading to disaster. An additional step to protect your sample is to set the Compliance Voltage limit of the CS580 below the maximum safe voltage that your sample can withstand.

The excitation current amplitude is set by the combination of Sine Out Amplitude from the SR860 and Gain on the CS580. For instance, as shown in Fig. 3a, to produce a 100 µA excitation current, the Sine Out amplitude is set to 1 V, with a CS580 Gain of 100 µA/V. To minimize distortion of the signal, the gain on the CS580 should be chosen to keep the output amplitude from the lock-in larger than 100 mV. The CS580 Triax configuration from Table 2 uses the inner shield of the triax for return current, and allows the entire current source circuit to float (i.e. disconnected from chassis ground). The outer shield remains connected to chassis ground, as indicated on the CS580 front panel diagram. The Slow Speed setting places a 470 pF capacitor across the current source output, low-passing the output signal with a cutoff frequency of $f_{\text{cutoff}} = \frac{2\pi}{R(470\ \text{pF}+C)}$ where R is the combined device, contact, and cable resistance, and C is the combined cable and load capacitance. If the excitation frequency $f > 0.1 f_{\text{cutoff}}$, use the Fast speed setting. For example, the "Slow" output current, if delivered to a 10 kΩ device with a 1 nF cable capacitance, has a f_{cutoff} of 427 kHz and can therefore be driven at up to 42.7 kHz. Unless the cable capacitance, device resistance, or drive frequency are high, Slow speed is likely sufficient.

All instrument settings are summarized in Tables 1 and 2. On the SR860, the Advanced filter (activated by holding down the "Slope/adv" button) achieves a shorter settling time for a given Slope, which is useful for faster parameter sweeps. Leave the filter as RC for a more calculable response, (see Appendix A of the SR860 Operation Manual for more information about filtering). The Time Constant should be set to something much longer than the period of the excitation current. For example, we often use a 300 ms time constant for a ~20 Hz drive. Increasing the time constant averages the signal for longer, leading to lower noise, but also increases the time for the output to respond to changes in the signal (the response times for different filter settings are listed in a table on page 157 of the SR860 Operation Manual).



(a) Configuration of SR860 and CS580 for four-point resistivity measurement. The Sine Out (V_{out}) from the lock-in is passed to the input of the voltage controlled current source. Current is delivered to the sample's I+ and I− leads with a triax cable (I±). The V+ and V− terminals are connected to the lock-in voltage inputs A and B, respectively.



(b) Breakout box which routes connection of current and voltage leads from the instruments to the cryostat and sample puck.

Figure 3

Table 1: SR860 Settings

Reference	
Source	Internal
Frequency	17.772 35 Hz
Phase	0°
Sine Out	
Amplitude	1 V
DC Offset	0 V
Input	
Select	Voltage
Voltage	A-B
Coupling	DC
Ground	Float
Time Constant	300 ms
Filter	
Slope	24 dB/octave
Advanced	On
Sync	On[1]
Input Range	Adjust to minimum without Overload
Sensitivity	Adjust to bring the largest signal you may see to about half of full-scale

Table 2: CS580 Settings

Gain	100 µA/V
Shield	Return
Isolation	Float
Speed	Slow
DC Current	0 µA

Now that everything is connected, enable the current by turning on the Input and Output of the CS580. You should see a measurable signal on the SR860, stabilizing within a few time constants. Adjust the Input Range to the smallest value that does not lead to an overload, then adjust the Sensitivity to bring the largest signal you may see to around half of full scale. Note that if the Input Range overloads, the signal is clipped and will not provide a reliable measurement. If only the Sensitivity indicates an overload, the analog voltage outputs will saturate but the data collected on your acquisition computer will be reliable.[2]

Because the AC current amplitude (I in Eq. (1)) is held constant by the SR860 and the CS580 output, only the X and Y outputs (or R and θ outputs) of the lock-in need to be measured to calculate the sample's resistance. The X voltage should be used in the resistance calculation (ΔV in Eq. (1)), with Y used to monitor the phase. If the measurement is performed in the regime where θ is small, then using R or X voltage will yield similar results. If the signal is too noisy, one can increase the excitation current (checking that the measured resistance does not change due to heating), increase the time constant, or average multiple readings (see Computer Programming and Data Acquisition). If the data is still too noisy, a new thinner and/or longer sample may be needed.

You can adjust the display of your lock-in to show

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[1] The Sync Filter averages the demodulated signal over a complete cycle of the reference frequency f, therefore removing all signal components at multiples of f. This is particularly useful at very low frequencies when removal of the $2f$ ripple would require very long time constants (and therefore long measurement times). The Sync Filter is only available for detection frequencies <4.8 kHz. Do not use the Sync Filter on the older SR830 lock-in.

[2] The details of signal overloads depend on the specific model of lock-in being used. Consult your instrument manual.

the desired channels. The Screen Layout button cycles through available display layouts. Use the Config button to select the displayed channels (X, Y, R, and θ are default). I find the screen layout in Fig. 3a is useful to easily monitor the status of an experiment at a glance: a strip chart time scale of 30 s/div (providing 5 minutes of history). (Adjust the time scale to match the time to complete your parameter sweep). Plotting X, Y, R, and θ is standard, but I like showing the X_{noise} channel[3] to get a quick idea of the noise in my measurement.

You might want to adjust your drive frequency. Higher frequencies avoid $1/f$ noise and allow measurement of faster phenomena, but can lead to larger phase lag between reference and signal, which can obscure the intrinsic device resistance and reduce the signal-to-noise ratio of your measurement as more excitation current is shunted via the load capacitance. With a sample resistance R and a stray capacitance C measured at frequency f, one can expect a phase shift of order $\theta = 2\pi f RC$. For a quasi-DC resistance measurement, the phase should be small, ideally less than 5°, although this may not always be possible in practice. Additionally, never use a frequency shared by other devices.[4] As shown in Fig. 4, the FFT display is great for identifying problematic frequencies (see Appendix B of the SR860 Operation Manual). Generally, avoid any multiple of 50/60 Hz, radio station frequencies, frequencies of other measurements, etc. We tend to use prime number frequencies with a random decimal value such as 17.7235 Hz or similar.

Finally, additional lock-ins (for more complex multi-terminal devices) can be synchronized to the primary lock-in using either the front panel Sine Out (if using a large enough excitation voltage) or the rear panel “BlazeX” output configured to provide a square wave output. At low frequencies in particular, the BlazeX output should be used, as it is much easier to sync to a sharp edge than a slowly varying sinusoid.

Results and Data Analysis

As a practical example, we discuss our recent study of $CaNi_2$ and $Ca(Rh_{0.98}Ru_{0.02})_2$ [5]. We grew single crystals of each material, prepared the samples as thin plates, and attached wires with the method discussed above. Resistance was measured as a function of temperature, as shown in Fig. 5. $CaNi_2$ shows standard metallic behavior, while $Ca(Rh_{0.98}Ru_{0.02})_2$ also shows a superconducting transition at 6.2 K. In our $CaNi_2$ sample, at 300 K, with a 7.5 mA excitation current, the lock-in X channel read 7.98 µV, and the Y channel measured approximately 1% of this value (for a phase angle of ∼1°). This corresponds to a resistance of V/I = 7.98 µV/7.5 mA = 1.064 mΩ. The sample dimensions were $l_1 = 0.144$ mm, w = 0.614 mm, and t = 0.144 mm. Using these, we obtain a resistivity of $\rho = (wt/l_1)R$ = (0.614 mm × 0.144 mm / 0.144 mm) × 1.064 mΩ = 65.3 µΩ cm. The noise levels were 28 nV with a 300 ms time constant (an SNR of nearly 700), so no further averaging was required. No major surprises were encountered in these measurements [11], though multiple samples were measured to confirm the consistency of our results. Additionally, we took care to optimize the current level for signal while avoiding self-heating.

Figure 4: FFT of input signal to SR860. The cursor highlights the signal at the drive frequency. The 60 Hz mains pickup and higher harmonics of 60 Hz can also be seen. These frequencies should be avoided.

For metallic single crystals, RRR values can range between 1 and 10^4 [2], and typically fall between 15 and 200. The RRR of these materials was reasonably good at 23 and 14 for $CaNi_2$ and $Ca(Rh_{0.98}Ru_{0.02})_2$ respectively. For the superconducting sample $Ca(Rh_{0.98}Ru_{0.02})_2$, the RRR is calculated using the resistivity *just above* the critical temperature: RRR = ρ(300 K)/ρ(6.3 K). For both materials, the RRR was sufficiently high (i.e. impurity scattering was sufficiently low) to observe quantum oscillations using torque magnetometry.

The T^2 coefficient of the low-T fitting of ρ_{xx} is a critical measure of electronic correlations in the material, as it directly probes the electron-electron scattering strength [2, 12]. Additionally, we speculate that the change in slope around 100 K in $Ca(Rh_{0.98}Ru_{0.02})_2$ may be related to un-

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[3] Noise measurements generally require ∼200 time constants to settle, since they require a stable mean value from which to calculate the standard deviation.

[4] Somewhat amusingly, we once observed slow oscillations in a mechanical torque experiment at a lock-in measurement frequency of 1000 Hz. We eventually realized that the origin of this oscillation was a nearby turbo pump also operating nominally at 1000 Hz. The mHz difference between these two signals led to a beat frequency with a period of tens of seconds.

usual scattering behavior originating from the very large Fermi surface associated with a flat band at the Fermi level, but further characterization and studies are needed to draw definitive conclusions.

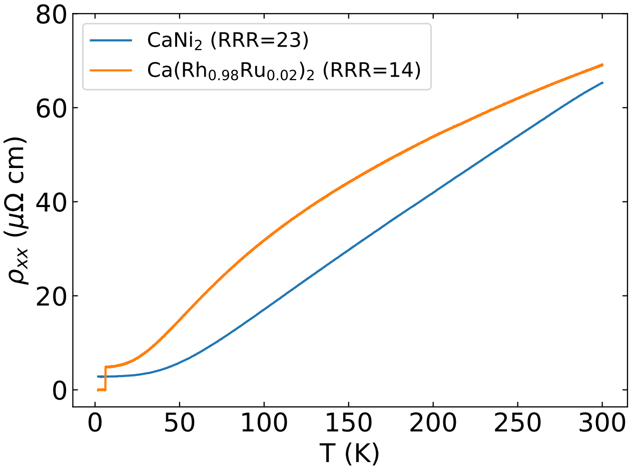

Figure 5: Measurement of the resistivity ρ_{xx} of two metals, CaNi$_2$ (blue) and Ca(Rh$_{0.98}$Ru$_{0.02}$)$_2$ (orange) as a function of temperature from 1.8 K to 300 K. The quality of each metal is relatively high, as indicated by the RRR, with the CaNi$_2$ being of slightly higher quality. Ca(Rh$_{0.98}$Ru$_{0.02}$)$_2$ additionally shows a superconducting transition at 6.2 K, while CaNi$_2$ remains metallic to base temperature. Figure reproduced from [5].

Cables and Grounding

The connection between your device and your instruments is just as important as the device and the instruments themselves. A full description of proper grounding and wiring for precision measurements is beyond the scope of this paper, but we include some important notes here. Use of shielded twisted pairs or coaxial cables are ideal. It is important to ensure that the shield of any measurement cable is grounded on at least one end, otherwise the shield is ineffective at screening noise pickup. The SR860 rear panel has a convenient Chassis Ground banana jack which we use to ground cable shields when using shielded twisted pairs. To avoid ground loops, the ground path should branch out like a star from a single central point, without cross-connections between branches. The larger the loop, or the larger the potential difference between separate local grounds, the worse the effects of the ground loop. Ideally, the measurement clean ground should be a dedicated earth connection used only by your measurement. The SR860 Ground configuration can be used to alleviate ground loops (see pages 51-52 of the SR860 Operation Manual).

A standard setup is shown in Fig. 6. Care is taken to provide a clean ground to the measurement apparatus, isolated from the control computer electrically by a communications isolator as computers often produce digital switching noise. We use the National Instruments GPIB-140B to isolate the communications, though similar products may be found for ethernet and USB. A breakout box can be used to connect the wiring that runs to the sample in the sample environment (for example, a superconducting magnet and temperature control system). This breakout box can have switches to ground or float each sample lead separately when changing the measurement wiring, or can simply allow access to the measurement leads and serve to keep the instrument rack tidy. The breakout box should ideally be grounded directly to clean ground or to only one instrument ground. Importantly, the shield of the cable running from the breakout box to the sample environment is only connected on one side. This prevents a large ground loop between the clean ground, the instrument rack, and the sample environment. The sample environment should only connect to a clean ground, with electrically noisy components—such as pumps and motors—electrically (and ideally vibrationally) isolated from the sample environment. The CS580 and SR860 are connected to clean ground through their power cables via the isolation transformer. For extremely precise measurements, the instrument rack and/or sample environment can be placed in a Faraday cage. If the sample environment is extremely sensitive to RF pickup (e.g. dilution refrigerators), the analog SR2124 lock-in can be used to eliminate emissions associated with CPU clock noise from a digital lock-in. Similarly, the CS580 has no running CPU clock except during brief moments when instrument settings are modified.

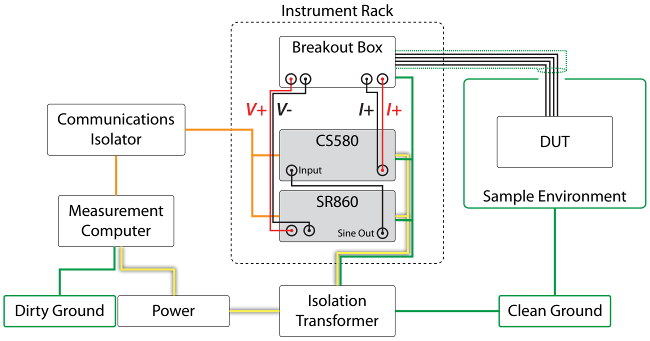

Figure 6: Suggested wiring for a low-noise electrical transport measurement. Ground cables are indicated in green, power in yellow, communications in orange, and signals in red/black. Note that ground is not connected between the sample environment ground and the breakout box ground to avoid a large ground loop.

Noise considerations

Electrical noise is characterized by a voltage spectral density $v(f)$, in units of nV/$\sqrt{\text{Hz}}$. This quantifies the noise as a function of frequency, and means that a measurement at frequency f with an equivalent noise bandwidth (ENBW) of Δf will contain a root mean squared (RMS) voltage fluctuation of $v(f)\sqrt{\Delta f}$. The ENBW is determined by the time constant and filtering of the lock-in, and can be easily obtained by tapping the front panel strip chart display. Additionally, a table for calculating the ENBW for various filter settings is provided on page 157 of the SR860 manual. For example, with a time constant of 300 ms and the 24 dB advanced filter, the ENBW = $0.81 \times 1/(2\pi \times 300\text{ms}) =$ 0.43 Hz. The overall RMS noise level can be measured by configuring the SR860 to display the X_{noise} and Y_{noise}. The noise density can then be calculated by dividing by the square root of the ENBW. In practice, a noise floor of a couple tens of nV/$\sqrt{\text{Hz}}$ or less usually means that a measurement is not suffering from glaring noise issues, and more extreme measures such as Faraday cages or analog electronics would be required to significantly lower the noise levels. Note that the SR860 input noise is itself 2.5 nV/$\sqrt{\text{Hz}}$ (at 1 kHz for the 10 mV Input Range).

Further discussion of electrical noise sources is available from page 54 of the SR860 Operation Manual and elsewhere, e.g. [13].

Troubleshooting

- Ensure the excitation current is not heating the sample by lowering the excitation current and seeing if the resistance value changes.
- If your signal is noisy (above a few tens of nV/$\sqrt{\text{Hz}}$), make sure that you avoid ground loops as discussed above. Make sure that the instrument rack is not connected to a dirty ground. Make sure that cable shields, breakout boxes, and cryostats are grounded on one side. Try measuring at a different frequency.
- If the noise level is low but your signal is still small, you may need to average longer, increase your excitation current, or prepare a sample with optimized geometry.
- If the voltage jumps during cooling/warming, or the electrical contacts disconnect entirely, you can pull out the sample and try to fix the contacts with new silver paint. Sometimes you can remove the old silver paint entirely and reapply.
- In situations where unloading, repairing, and reloading a sample is impossible, such as during a time-constrained measurement, bad contacts can occasionally be repaired at low temperature through "current annealing." A current or voltage not to exceed 10 mA or 10 V can be applied by the CS580 via the DC offset current for one second at a time. This technique can also destroy contacts and fragile devices though, so it should be reserved for cases where the device is unusable otherwise.

Acknowledgements

Sample fabrication, transport measurements, data collection, and discussion of results were provided by Joshua Wakefield.

References

1. Singleton, J. *Band Theory and Electronic Properties of Solids* 117–135 (Oxford University Press, Oxford, UK, 2001).
2. Kittel, C. *Introduction to Solid State Physics* 8th ed. (ed Johnson, S.) 147–156, 209–213 (Wiley, New York, NY, 2005).
3. S. M. Girvin, K. Y. *Modern Condensed Matter Physics* 164–197 (Cambridge University Press, Cambridge, UK, 2019).
4. Devarakonda, A. *et al.* Clean 2D superconductivity in a bulk van der Waals superlattice. *Science* **370,** 231–236.
5. Wakefield, J. P. *et al.* Three-dimensional flat bands in pyrochlore metal CaNi2. *Nature* **623,** 301–306.
6. Suzuki, T. *et al.* Large anomalous Hall effect in a half-Heusler antiferromagnet. *Nature Physics* **12,** 1119–1123.
7. Ye, L. *et al.* Massive Dirac fermions in a ferromagnetic kagome metal. *Nature* **555,** 638–642.
8. Suzuki, T. *et al.* Singular angular magnetoresistance in a magnetic nodal semimetal. *Science* **365,** 377–381.
9. Kang, M. *et al.* Dirac fermions and flat bands in the ideal kagome metal FeSn. en. *Nat. Mater.* **19,** 163–169.
10. Stanford Research Systems. *About Lock-in Amplifiers*.
11. Matthias, B. T. & Corenzwit, E. Superconducting Alkaline Earth Compounds. *Physical Review* **107,** 1558–1558.
12. Baber, W. G. The contribution to the electrical resistance of metals from collisions between electrons. *Proc. R. Soc. Lond. A* **158,** 383–396.
13. Ott, H. *Noise Reduction Techniques in Electronic Systems* ISBN: 9780471850687 (Wiley, 1988).

About the Author

Paul Neves is a graduate student in the group of Prof. Joseph Checkelsky at the Massachusetts Institute of Technology. Paul is a sixth year Ph.D. student studying experimental condensed matter physics. He specializes in studying exotic electronic and magnetic phases in quantum materials with techniques including high magnetic field measurements, angle resolved photoemission spectroscopy, and neutron scattering.

Figure 7

Computer Programming and Data Acquisition

To record data and control the sample environment, a measurement computer is used. Communication with the SR860 can be performed over GPIB, RS-232, USB, or Ethernet (see Chapter 4 of the Operation Manual for more details). Most commonly-used programming languages can communicate over these protocols, including Python, MATLAB, and LabVIEW. The most important commands for data acquisition are `OUTP? [j]`, `SNAP? [j, k]`, and `SNAPD?` (see pages 132-133 of the manual). These commands allow one to programmatically access the measured channels of the lock-in: X, Y, R, and θ for example. These values can be recorded in a data file, along with any other important parameters such as sample temperature or magnetic field, to be plotted and analyzed later. Example minimal MATLAB and Python code snippets are provided below.

MATLAB Code Snippet

```
% Define the GPIB address
gpib_address = 5;

% Create and connect to the SR860
sr860 = gpib('NI', 0, gpib_address);
fopen(sr860);

% Query the X value
fprintf(sr860, 'OUTP? 0');

% Read the output
x_value = fscanf(sr860)

% Close the connection
fclose(sr860);
delete(sr860);
```

Python Code Snippet

```
import visa
rm = visa.ResourceManager()

# Define the GPIB address and connection string
address = 5
resourceString = ("GPIB::%d::INSTR"%address)

# Create and connect to the SR860
sr860 = rm.open_resource(resourceString)

# Query X value and convert to float
x_value = float(sr860.query("OUTP? 0")

# Close the connection
sr860.close()
```

If you are interested in instrument control using Python, check out the **SR860 Python Instrument Driver** from SRS on GitHub, as well as the series of **getting started videos** on YouTube.

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