Electrical resistivity is a fundamental material property and is crucial for understanding electronic behaviour in a material. The simplest electrical resistance measurement is a 2 terminal DC measurement of voltage due to an applied current. This method is prone to noise because: 1. The system is being driven at low frequency, and thus a substantial amount of 1/f noise is introduced. 2. Lead and contact resistance 3. Thermal offsets

![[Pasted image 20251127035603.png]] (Source:[1])

Here, we discuss the four-terminal AC resistance measurement as an alternative to the simple two-probe DC measurement.

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There are two main advantages of the four-point AC method over the more rudimentary two-probe method - 1. The four-point geometry removes the effects of contact resistance, allowing a measurement of the intrinsic device resistance. 2. The measurement of an AC voltage at a fixed frequency of excitation current allows the use of Lock-In measurement, which provides an effective narrow bandwidth extraction of the signal. This reduces the noise in the measurement greatly. Moreover, the measurement using AC provides some isolation from the thermoelectric voltages present in the DC measurements.

Contact resistance

When two metal surfaces touch, they normally do not make contact across the entire macroscopic contact surface area (A_m). Instead, they touch only at microscopic high points on the surfaces called **asperities**. The sum of all the contact areas from the asperities is called the real contact surface area (A_r). Normally, $A_r << A_m$. The current lines must squeeze together to pass through the asperities, and this is the primary reason for the creation of contact resistance and is called the "Constriction Resistance". There are two main regimes involved in modelling how the asperities affect contact resistance, and they are determined by comparing the radius of the spot of asperities contact (a) and the electron mean free path length (l). 1. Diffusive regime ($a >> l$): Here, the electrons will scatter several times as they pass through the contact. Thus, the transport is diffusive and is governed by the Maxwell equations. The resistance contribution in this case is given by $R_{diffusive} = \frac{\rho}{2a}$. 2. Ballistic regime ($a << l$): Here, the electrons travel through the contact spot without scattering. Thus, the resistance is no longer due to the scattering but rather due to the number of quantum channels available for the electron wavefunction to transmit. This is Sharvin resistance, and is derived from semiclassical transport theory to be $R_{ballistic} = \frac{4\rho l}{3\pi a^2}$ Normally, metal-metal contact resistance is ohmic. But due to the massive constriction of current to the asperities, there is a large current density present there. This leads to a significant amount of Joule heating. Also of interest is the fact that thermal fluctuation can result in fluctuations in A_r - which can cause a fluctuation in the effective resistance of the device seen. This is a potential source of 1/f noise in the system. Considering all these effects, it is crucial to measure the submilliohm resistance using a 4-point method as otherwise we would be measuring the contact and not the device resistance itself.

Preparation of sample for 4-point measurement

Note that minimising the contact resistance is good practice even in the case of 4-point measurements, as contact resistance can result in ohmic heating of the sample and introduce noise.

Ideally, contacts should be cleaned properly before making connections. Even with silver conductive paint at contact junction, contact resistances can be as large as 10Ω.

[1] Four-Point AC Resistance Measurements, Paul M. Neves, SRS Technique Paper TP2401
[2] Four-Point AC Resistance Measurements, Paul M. Neves, SRS Technique Paper TP2401

BNC Cables

The Bayonet Neill-Concelmann (BNC) cable is a coaxial RF cable that is designed for use in scientific data collection. The dimensions and material of the BNC cables are designed to provide a characteristic impedance to the signal. This reduces the phenomena of signal reflection at the connection point. The coaxial design of the cable acts as a Faraday cage, essentially shielding the inner wire from external electromagnetic interference. Normally, an important aspect of using BNC cables to relay a signal is **impedance matching**. When a signal is relayed down a BNC cable and it reaches the device/load, the signal can either be absorbed by the load or it can be reflected back the wire. The behaviour is quantified by the reflection coefficient, defined as:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Where Z_L is the load impedance, and Z_0 is the cable impedance (usually specified very accurately). Ideally, we would want $\Gamma = 0$, which requires $Z_L = Z_0$, which is the impedance matching criteria. If we have $\Gamma \neq 0$, we end up having standing waves and jitters in the cable, which obviously affect measurements significantly. When is matching required? The effects of impedance mismatch become apparent only when the cable acts like a transmission line. This happens when the cable length is significant compared to the signal's wavelength. A rule of thumb is that matching is required when we have:

$$\text{Cable length} > \frac{\text{Wavelength}}{10}$$

In our case, we use driving frequencies upto $\approx 100kHz$. This corresponds to a wavelength of $\approx 300m$, and a threshold (from the rule of thumb) of $30m$. Since the cables we use are significantly shorter, impedance matching is not something that we concern ourselves with here. ## Setting up instrument It is to be noted that in our experiment we did not have access to a modulated constant current source that could generate a clock synchronisation signal compatible with the Lock-In Amplifier provided. Thus, we resorted to using the Lock-In Amplifier's internal reference signal to drive a modulated current through the device being measured. The drive frequency influences the measurement in many ways. A larger driving frequency may avoid significant 1/f noise and allow the measurement of faster phenomena (with reasonable time constants), but it can lead to larger phase lag between the reference and the signal which may obscure the intrinsic device resistance and reduce the signal to noise ratio of the measurement as more current is shunted through the stray load capacitance. With a sample resistance R and a stray capacitance C measured at some frequency f, we will observe a phase shift of the order:

$$\theta = 2\pi fRC$$