
Coulomb blockade thermometer measurements

Using the TeslatronPT Plus with SampleProtect

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1. Introduction

Coulomb blockade thermometry provides a method for measuring temperature which, unlike resistive thermometry, does not require initial calibration and is intrinsically independent of any applied magnetic field: making such thermometers attractive for precision measurements of quantum materials in low-temperature, high magnetic-field environments.

However, measuring these devices can be challenging due to the need for low-noise signalling to both prevent sample heating, and to ensure the accuracy of the temperatures extracted from the measurements. In addition, the devices are susceptible to damage by ElectroStatic Discharge (ESD) and must be protected from charge build-up.

This application note presents measurements of a Coulomb blockade thermometer in a **Teslatron**PT Plus system down to temperatures of 1.5 K and in magnetic fields of up to 12 T. A short introduction to the concepts in Coulomb blockade thermometry is provided in section 2 and details of the system setup are given in section 3. The results of the measurements are given section 4 and details of supporting measurements are provided in the appendices.

2. Background

Coulomb blockade thermometers (CBTs) rely on the Coulomb blockade effect [1] to provide a method for directly determining the temperature, without an external calibration. The thermometer is also unaffected by external magnetic fields.

These devices consist of arrays of tunnel junctions formed from metallic islands, separated by insulating barriers, through which electrons tunnel to produce a current. At very low temperatures, in the strong Coulomb blockade regime, the charging energy of these islands, E_C , leads to insulating behaviour. However, at higher temperatures thermal fluctuations enable tunnelling, producing a dip in the differential conductance ($G = dI/dV$) around zero bias whose form can be described exactly [2].

The full width at half maximum, Γ , can be used to determine the temperature in the high temperature limit ($k_B T \gg E_C$) as

$$T = \frac{\Gamma e}{5.439 N k_B}, \quad (1)$$

where N is the number of tunnel junctions in the CBT array. The theory can be extended to lower temperatures [3] and low-resistance CBTs [4]. Regardless of junction resistance, the equation relating

the temperature to Γ depends only on fundamental constants, allowing the CBT to be used as a primary thermometer.

Additionally, the conductance dip depth, Δ , (relative to the infinite bias conductance value) can be used to determine the temperature as

$$T = \frac{E_C}{6k_B\Delta}. \quad (2)$$

Here $\Delta = 1 - G_0/G_T$, where G_0 is the conductance at zero bias and G_T is the infinite bias conductance.

The charging energy is a tuneable parameter, based on the junction geometry [5], which allows the operational temperature range of the sensor (which typically spans several orders of magnitude) to be adjusted to suit the intended application during the fabrication stage.

The temperature can also be derived from measurement of G_0 alone if the values of E_C and G_T have already been determined; this provides a second thermometry mode that requires only a measurement at zero bias, which can allow for faster temperature measurements (that are still independent of magnetic fields).

3. Method

Measurements were performed using the Quantum Design Oxford TeslatronPT Plus [6] (see also the ‘About TeslatronPT Plus’ section at the end of this document). Details of the measurement configuration of this system have been provided previously¹.

The CBT devices were integrated using a Universal Measurement Probe and **SampleProtect**® unit, and measurements performed by customising standard template scripts meaning minimal preparation was required to begin measurements. The following sections detail the fabrication of the CBT devices and describe the TeslatronPT Plus setup used.

3.1. CBT devices

The fabrication of the CBTs is as described in [7]. Broadly, the devices are fabricated from Al/Al₂O₃ junctions produced using a shadow mask lithography process. This uses two separate Al evaporations, at different angles, separated by an oxidation step in order to build up overlapping Al structures with an oxide layer between them; forming the tunnel junctions as shown in figure 1.

¹For additional details please refer to the Quantum Design Oxford Application Note *Collection, analysis and presentation of Shubnikov-de Haas oscillation data*

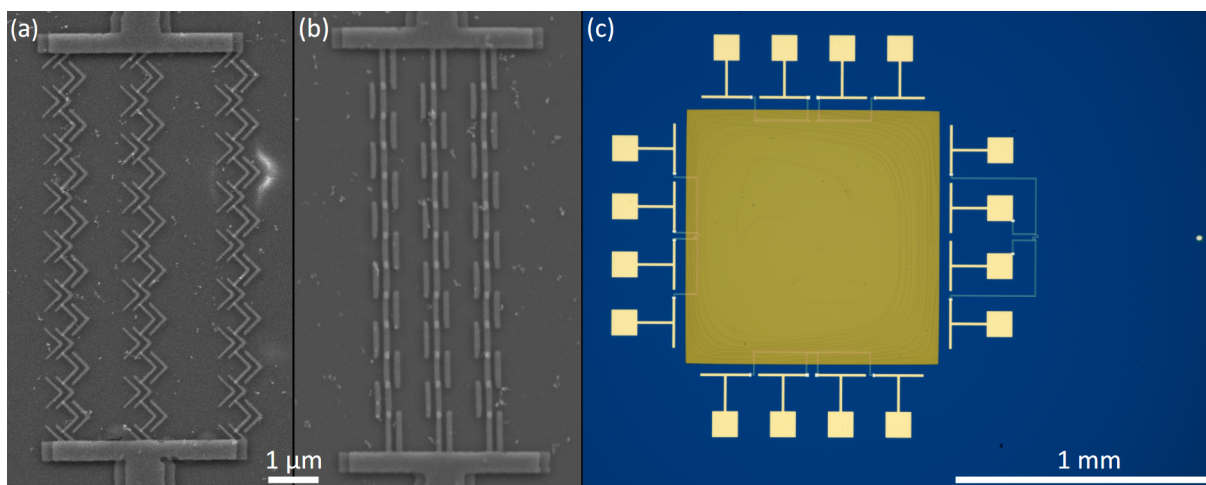


Figure 1: Images of the CBT devices. Panels a and b: Scanning electron microscopy images at 10,000 $\times$ magnification. Here an accelerator voltage of 5 kV was used with secondary electron detection. The working distance was 5.5 mm for the ‘chevron’ type CBTs shown in (a) and 6.1 mm for the rectangular CBTs in (b). Panel c: Optical microscope image at 5 $\times$ magnification showing the overall device layout.

3.2. Instrumentation

Measurements of the CBT device as function of temperature and magnetic field were performed in the Quantum Design Oxford TeslatronPT Plus [6] **Cryofree**[®] open-architecture, low temperature measurement system; incorporating a variable temperature insert cryostat with a temperature range of 1.5 K to 300 K and, in this case, a 12 T solenoid magnet.

The CBT chip was held in a 20-pin leadless chip carrier (LCC20), which can be easily mounted to a measurement cell (see figure 2). The cell connects to the probe which can then be loaded into the TeslatronPT Plus system.

The temperature of the chip was measured with the sample cell thermometer, a calibrated Lake Shore Cernox CX-1050 temperature sensor [8]. The Cernox sensor is mounted a few centimetres away from the CBT devices. Thermalisation of the CBT chip and Cernox was achieved by operating the sample holder in static helium exchange-gas.

All magnetic fields were applied along the axis of the probe and therefore in the plane of the CBT.

The breakout boxes, Lake Shore measurement instruments and the measurement server (from which measurement scripts are run and where the resulting data are stored) are mounted in a 19” rack. A schematic of the measurement setup, including some of the measurement rack components, the probe and the CBT sample, is shown in figure 2.

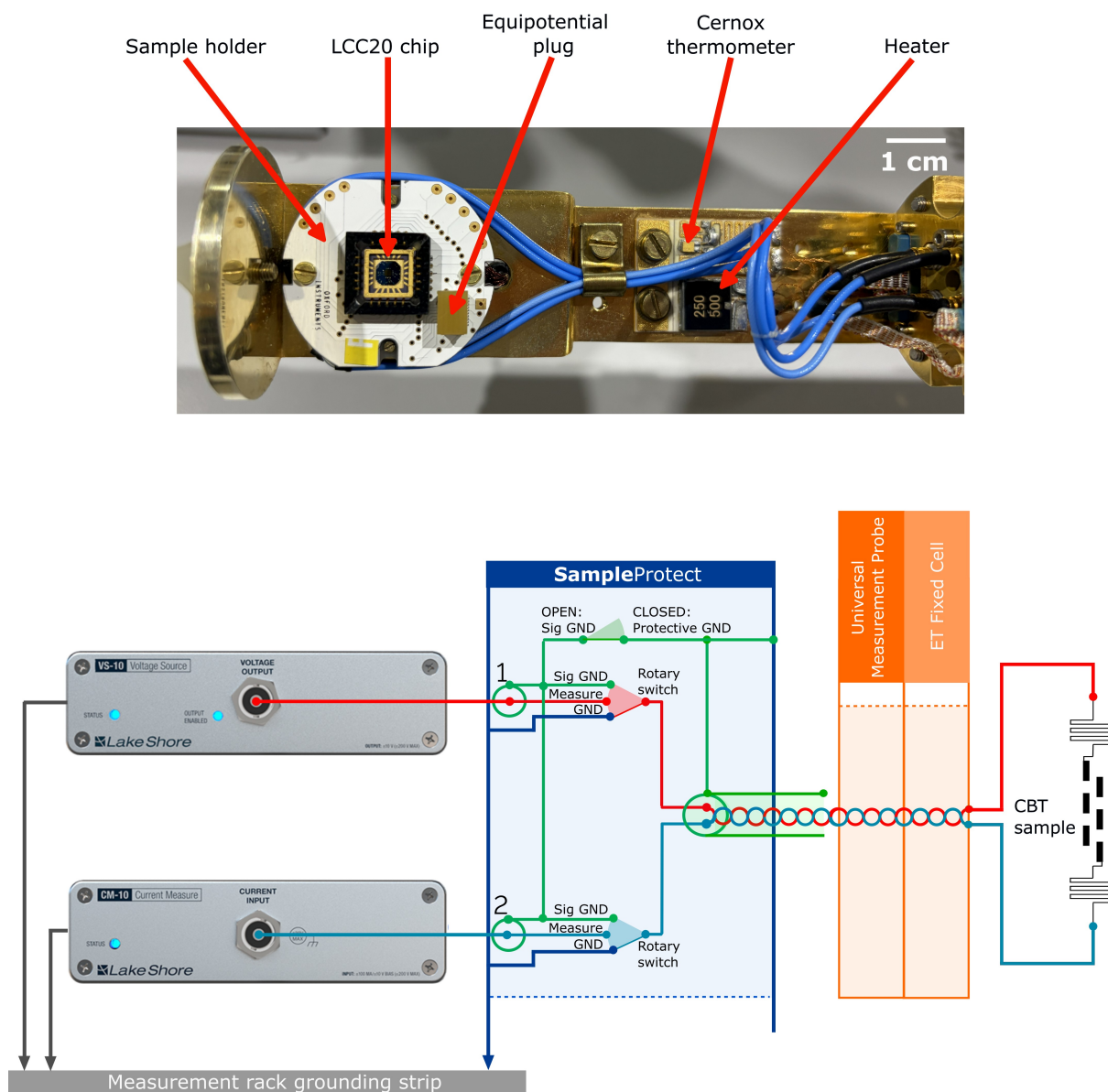


Figure 2: Top panel: the electrical transport cell with the CBT chip in an LCC20 carrier mounted on a sample holder. The equipotential plug protects the CBT from ESD damage when the probe is disconnected from the measurement electronics. The Cernox thermometer and probe heater are also shown. Bottom panel: schematic of the CBT measurement, showing the Lake Shore M81-SSM voltage source (VS-10) and current measure (CM-10) modules, the SampleProtect unit, the Universal Measurement Probe with the Electrical Transport (ET) Fixed Cell and the connections to the CBT sample. The SampleProtect utilises ‘make before break’ rotary switches to prevent charge build-up on the CBT. In this case, the CBT was grounded by setting the switches to protective ground (GND).

Since CBTs are sensitive to ESD, the probe was connected to a SampleProtect unit [9] to allow the CBT to be grounded when not being measured. The SampleProtect switches are ‘make before break’, to avoid charge build-up damaging the CBT when connecting or disconnecting contacts from ground. The equipotential plug on the sample holder protected the CBT during the setup of the probe outside the cryostat, when it was disconnected from the electronics.

Two-wire differential conductance measurements were performed using a Lake Shore M81-SSM synchronous source measure system [10] using voltage source (VS-10) and current measure (CM-10) modules in lock-in mode.

For all measurements, the lowest possible current and voltage ranges were used, with the CM-10 operating in high-reserve mode for the input filter and with a 1 kHz cut-off for the low-pass filter.

3.3. System control and data handling

The TeslatronPT Plus system parameters, such as temperature and field, are controlled and recorded using DECS [11]. DECS, along with the measurement instruments, can be directly controlled using QCoDeS [12], a Python-based framework which provides drivers for many scientific instruments, including the TeslatronPT Plus and the Lake Shore M81. QCoDeS also encompasses data acquisition and storage in databases, which also contain extensive metadata from the instruments.

The measurement server provides a JupyterLab environment to run notebook based scripts to automate measurements, record and store data, and to subsequently analyse it. During measurements, data can be viewed using Grafana dashboards which read directly from the database. Metadata and measurement parameters can also be displayed, allowing users to quickly view multiple experimental runs and identify datasets for further analysis.

Template measurement scripts and corresponding dashboards are provided on the measurement server, and can be easily adapted for custom experiments.

3.4. Measurements

To assess the noise level in the CBT measurement chain, a frequency spectrum of the current across the device with no applied voltage was recorded (see section A.1). A discrete Fourier transform was applied to the current trace as a function of time to obtain a frequency spectrum and normalised to give the current spectral density. From the results of this analysis a suitable lock-in modulation frequency, away from any residual noise peaks, was chosen for the conductance measurements.

To record the conductance dips, a small (compared to I') AC modulation voltage (at the lock-in detection frequency) was applied for a range of DC bias voltages across the conductance dip. These potentials

were supplied by the VS-10, and the resulting currents measured by the CM-10. The differential conductance was calculated from the magnitude of the demodulated current signal by dividing by the amplitude of the lock-in modulation voltage.

4. Results

4.1. Low-temperature conductance curves

Before extracting temperatures from differential conductance measurements, the curves are first characterised. A conductance curve measurement is taken and a fit to these data (from equation 1) used to extract values for G_T and E_C . If the CBT is to be operated in its secondary thermometry mode, such a calibration is necessary since G_T and E_C are required to determine the temperature from G_0 via equation 2.

In the results presented here, the values of G_T and E_C determined from this initial measurement were used for all subsequent analysis of data recorded at different temperatures.

The conductance dip used for this initial calibration is plotted in figure 3. Note that no background has been subtracted here, since its bias dependence is small in this voltage range (see section A.2).

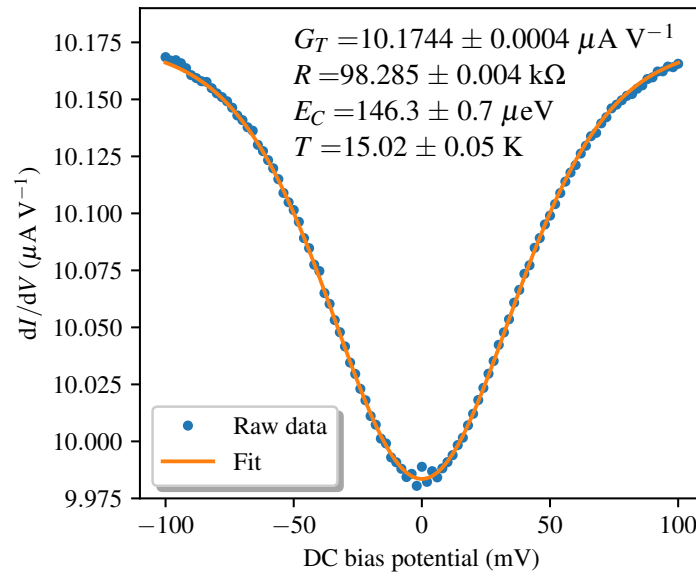


Figure 3: Conductance dip used for calibration of the CBT. Here the temperature = 15 K, frequency = 67 Hz, lock-in amplitude = step size = 2 mV, delay time between points = 3 s, averaging time = 1 s, current range = 10^{-6} A.

These data show a high signal-to-noise ratio and good agreement with the theory. The extracted temperature is within $\sim 0.1\%$ of the Cernox temperature set-point, and the 20 mK variation is similar to the long-term accuracy expected from the Cernox [8].

The E_C value of $146.31 \mu\text{eV}$ is equivalent to 1.69 K, meaning the CBT can operate (in principle ²) as a thermometer above temperatures of about 680 mK, below which the equations used to describe its behaviour would no longer be valid.

4.2. Temperature and field dependence

According to the models in section 2, the conductance dips should become shallower and wider as the temperature increases. This behaviour is demonstrated in figure 4, where fits to the data are also plotted. When extracting temperatures from the conductance dips, the values of G_T and E_C are fixed to those derived from the calibration measurement shown in figure 3. The temperature recorded with the Cernox temperature sensor on the probe remains stable throughout the measurement, with the temperature only deviating from the setpoint by up to a few mK. The Cernox sensor accuracy is better than ± 20 mK for temperatures below 20 K [8].

The temperatures extracted from the fits to the conductance dips are consistent with the Cernox readings at 10 K and 20 K. There is a greater discrepancy at lower temperatures, with the slight widening of the conductance dip tails (as seen in the raw data compared to the fits) suggesting a level of self-heating³ [13].

The distance between the CBT chip and the Cernox thermometer (see figure 2) may also have a greater impact on the thermalisation between the two at lower temperatures. Additionally, at the lowest temperatures, the system is approaching the superconducting transition of the Al used in the construction of the junctions in the CBT, this is discussed further in section A.3 and section A.4.

The extracted temperatures and further results at 1.7 K and 8 K are plotted as a function of the Cernox temperature in figure 4. Overall, there is a good correspondence between the two (physically separated) temperature sensors across the temperature range.

²Note, the Al junctions used in the construction of these CBT will become superconducting at around 1.2 K which places a lower limit on their operation (at least in zero magnetic field).

³Note, at the lowest temperatures it is more usual to measure G over a narrower range of bias potentials than those used in the plots to limit the Joule heating away from the conductance minimum.

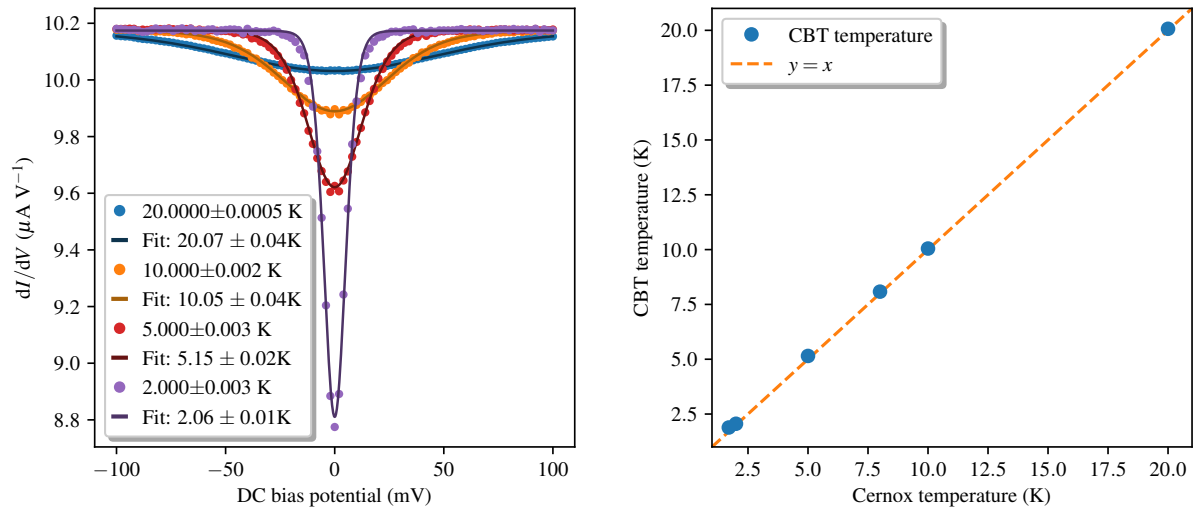


Figure 4: Left panel: Temperature dependence of conductance dips for the CBT. Fits to the dips at each temperature are also plotted. For these fits, G_T and E_C values are fixed at the values extracted from the calibration in figure 3, and the temperature is the only parameter allowed to vary. The recorded average temperature and its range and the temperatures extracted from the fits with errors are given in the legend. Frequency = 67 Hz, step size = 2 mV, delay time between points = 3 s, averaging time = 1 s, current range = 10^{-6} A. Lock-in amplitudes: 3 mV at 20 K, 1 mV at 10 K, 0.5 mV at 5 K, 0.2 mV at 2 K. Right panel: the agreement between the temperatures extracted from the CBT conductance dip and those recorded by the Cernox temperature sensor at six different temperatures.

Since there is no dependence of the dip width or depth on a magnetic field in equation 1 or equation 2, the conductance dips should not change shape as the field is increased. A series of measurements taken between 0 T and 12 T at the base temperature of the system are plotted in figure 5. There is no obvious variation in the form of the dips, and the deviation also shows no apparent field dependence. The standard deviation between the individual temperature measurements is < 3 mK. These data also suggests that the field dependence of the rest of the circuit (excluding the CBT itself) is minimal (see the magnetoresistance measurements in section A.3).

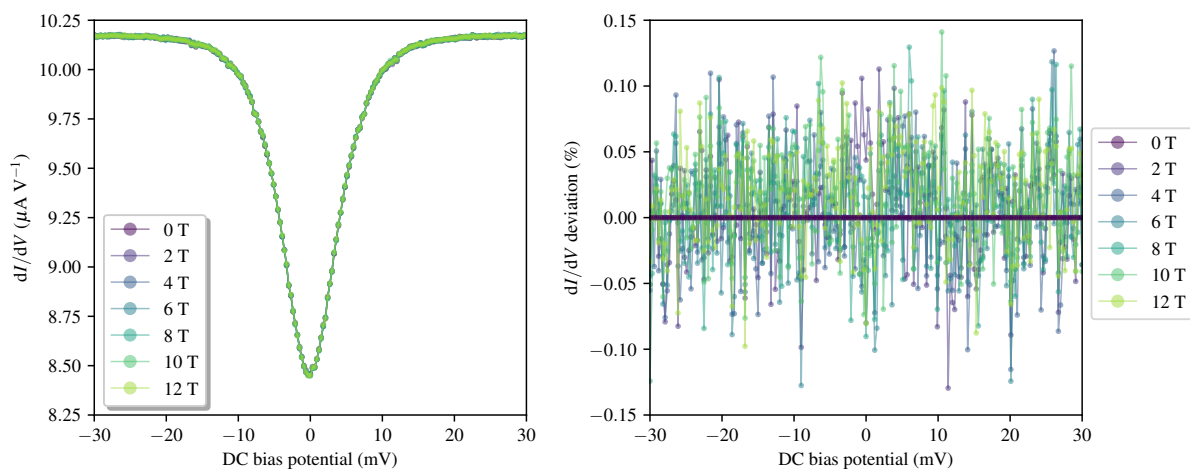


Figure 5: Left panel: Conductance dips of the CBT between 0 T and 12 T at base temperature ~ 1.5 K. Frequency = 67 Hz, lock-in amplitude = 0.15 mV, step size = 0.3 mV, delay time between points = 3 s, averaging time = 1 s, current range = 10^{-6} A. The system cooled down during each measurement by up to 20 mK, after warming slightly during the magnet ramp. Right panel: deviation of the dI/dV values for each dip from the zero-field dip, expressed as a percentage of the zero-field conductance value at each bias voltage.

5. Conclusions

High quality measurements of sensitive Coulomb blockade thermometer devices were made using a TeslatronPT Plus measurement system utilising SampleProtect.

The low-noise signal chain allowed for accurate determination of the probe temperature from Coulomb blockade conductance dips, and the temperature and field stability of the TeslatronPT Plus enabled such measurements to be performed over a wide range of parameter space.

These measurements confirmed the expected temperature sensitivity and field independence of the Coulomb blockade devices, demonstrating the viability of these sensors being deployed as thermometers in low-temperature and high magnetic-field environments.

6. References

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About TeslatronPT Plus

TeslatronPT Plus is an open-architecture low-temperature measurement system that builds on Quantum Design Oxford's proven cryogen-free low-temperature and superconducting magnet technology. It offers fully automated control of temperature and magnetic field parameters, with integrated data logging within our software environment. The system seamlessly integrates with measurement instrumentation, such as that from Lake Shore (the M81 & M91) and other third-party devices, so is easily configurable across experimental setups.

With open-source Python measurement scripts TeslatronPT Plus simplifies instrument management, enabling automated measurement sequences and secure data handling. Combining advanced hardware with powerful software tools, it delivers a simple, flexible, and future-proof solution for electrical transport measurements at low temperatures and in high magnetic-fields.

Find out more about [Quantum Design Oxford - TeslatronPT Plus](#)



The acquisition of the data presented in this document; the associated analysis of those data; and all of the typesetting and formatting of this document has been performed within the Jupyter environment provided with the Quantum Design Oxford measurement server.

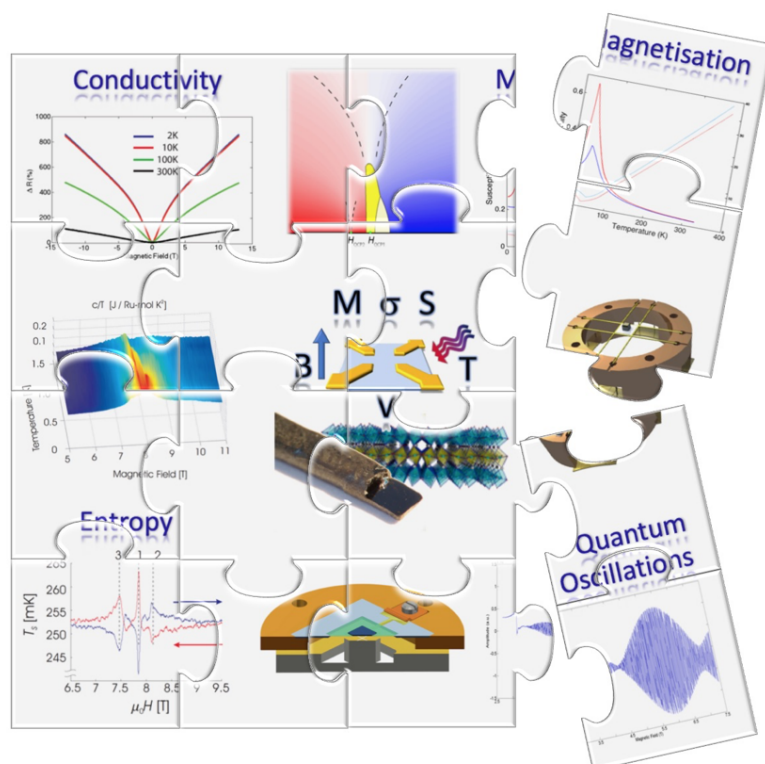
About quantum materials research at the University of St Andrews, UK

The Rost lab is working on unconventional phases in materials with strong electron correlations (quantum materials). A key focus is on the new opportunities opened up by the possibilities of measuring thin-film materials and single crystals of microscopic dimensions. As part of the Designer Quantum Materials Centre of the School of Physics and Astronomy they are using and developing bespoke experiments enabling the measurement of fundamental quantities such as magnetisation, entropy, strain and magnetoconductivity.

They recently built a SiN membrane based calorimeter specifically designed for microcrystal thin film work [7]. Both the thermometer and heater are realised by self-calibrating, magnetic-field independent Coulomb blockade thermometers. The nonmagnetic components enable the calorimeter to be used for both magnetocaloric effect and specific heat measurements with the former only requiring a thermometer. Addenda heat capacities as low as 100 fJ K^{-1} at 1 K can be realized. The setup enables heat capacity measurements at temperatures below 50 mK and in magnetic fields above 15 T for single crystals smaller than $100 \mu\text{m}$.

Max Pelly recently completed his PhD in the Rost group.

Further details of the work undertaken in the group can be found [here](#).



A. Appendices

A.1. Current noise spectra

A noise spectrum recorded at 220 K, during cooldown, is shown in figure 6. Also plotted are the noise density specification for the Lake Shore M81 at 1 kHz for a current range of $1 \mu\text{A}$ in high reserve mode [14], and the expected Johnson noise across a resistance the same as that of the CBT ($86 \text{ k}\Omega$) which is slightly below the noise floor of the instrument. The measured noise level is consistent with the bare instrument specification, highlighting the low-noise signal chain.

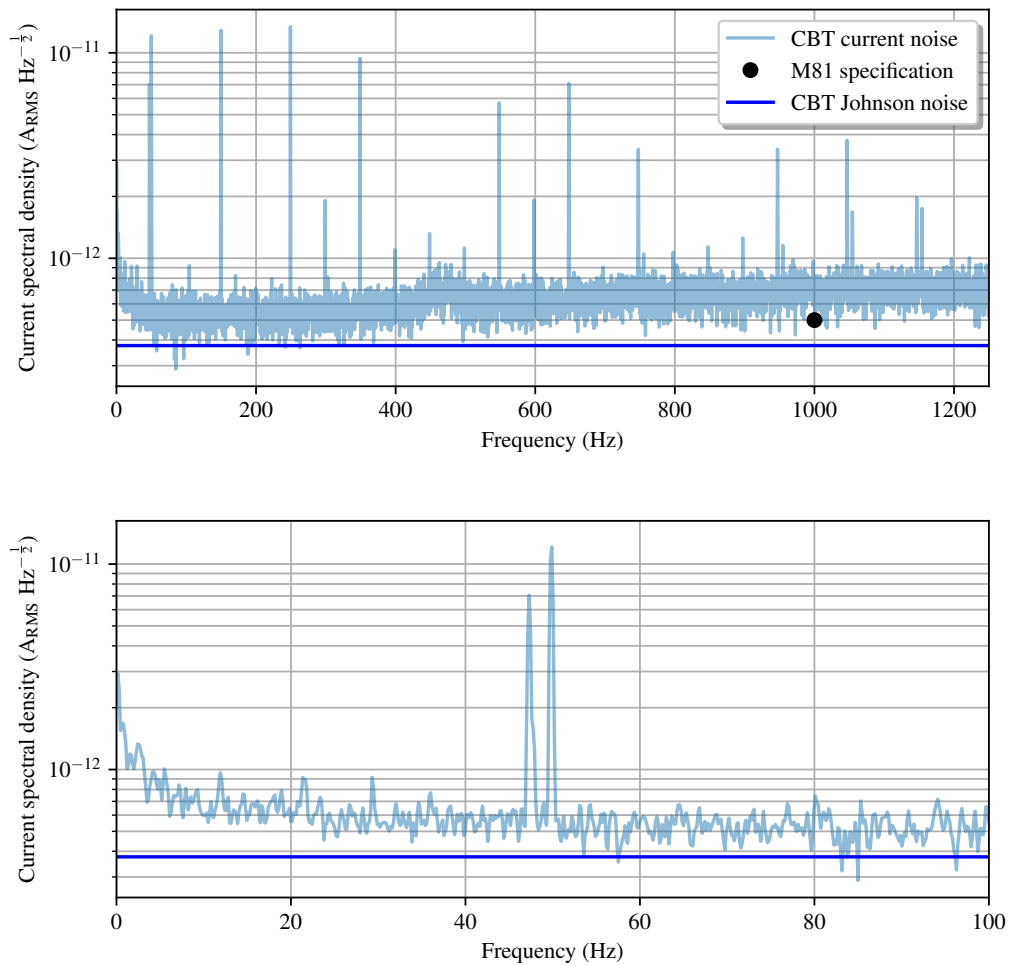


Figure 6: Current noise spectral density for the CBT at 220 K. An average of 20 measurements is plotted. Number of points = 2^{14} , sampling rate = 2.5 kHz. Top panel: full spectrum up to 1.25 kHz. Bottom panel: low frequency region up to 100 Hz. The black dot shows the Lake Shore specification for the noise density at 1 kHz for the CM-10 module operating in high reserve mode for a current range of 10^{-6} A . The dark blue line shows the expected Johnson noise across an $86 \text{ k}\Omega$ resistor.

The low frequency region of this spectrum was used to choose a lock-in frequency for measurements. The region between 0 Hz and 100 Hz is also plotted in figure 6. Between 60 Hz and 80 Hz there appear to be no noise peaks above the baseline level: and so a frequency of 67 Hz was used for the lock-in amplifier.

This measurement was repeated once the probe had cooled to 1.9 K, near its base temperature. The noise peaks were unchanged, so the lock-in frequency chosen at 220 K is still acceptable for all low-temperature measurements.

A.2. Conductance background

The insulating barrier through which the electrons in a CBT have to tunnel has a height of about 2 eV [15]. The models in section 2 assume an infinitely high tunnelling barrier, which is effectively true at low applied bias voltages but not when the bias across the CBT becomes higher. The result is a bias-dependent background conductance which can change the overall shape of conductance dips.

This effect is only significant at higher temperatures, since conductance dips at low temperatures are so narrow that only low bias voltages are required.

There are no accurate theoretical models to describe the background, but it can be corrected for by obtaining a conductance measurement over a large range of bias voltages at low temperature (hence with a narrow conductance dip) and fitting a polynomial to this measurement (in the region away from the conductance dip), which can then be subtracted from subsequent high-temperature measurements [5].

A fit to the bias-dependent background for the CBT at 1.7 K is shown in figure 7. The bias was varied between ± 500 mV and all points within ± 50 mV were excluded from the fit. The polynomial function fitted to the data includes terms with degree 0, 1, 2, 4 and 6; the 1st degree term allows for any asymmetry in the background.

For the conductance dips in the calibration measurements and the temperature and field dependences in section 4, only bias voltages up to ± 100 mV are used. Subtracting the background from the conductance dips in figure 4 changes the temperature calculated from the fit by up to about 0.3% for each temperature. Since the bias dependence up to ± 100 mV of the background is small and there is no apparent significant deviation from a flat line in the measurements in this region (away from the dip), no parabolic background subtraction has been used to correct any of the dips.

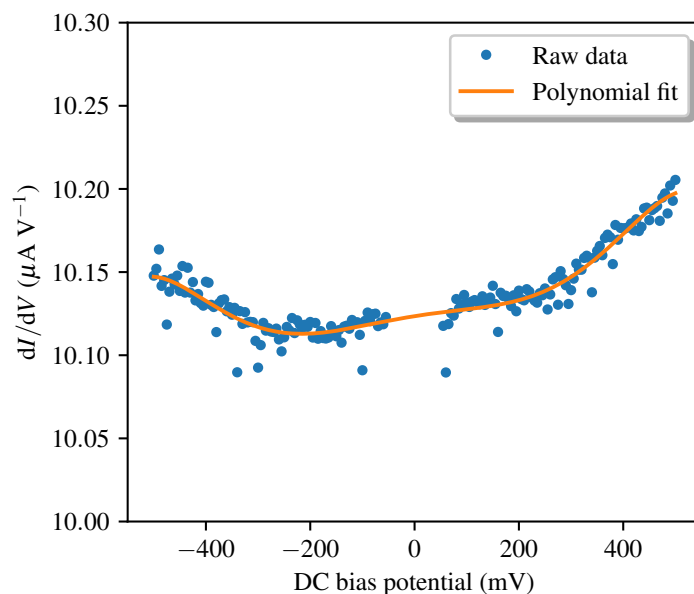


Figure 7: Fit of a polynomial background to a CBT conductance dip. Any points between ± 50 mV (not plotted) are removed from the fit. Temperature = 1.7 K, step size = 5 mV, lock-in amplitude = 0.2 mV, frequency = 67 Hz, delay time between points = 3 s, averaging time = 1 s.

A.3. Temperature and field dependent corrections

Al meanders were deposited on the CBT chip to allow the resistance of the circuit elements as a function of temperature and magnetic field to be investigated. These are larger than the meanders connected to the CBT itself for thermalisation, but can therefore be used to give an upper bound on the effects of the wiring on the measured behaviour of the CBT.

The temperature and field dependences of the resistance of the Al meander circuit (including the Al meander, the wiring along the body of the probe and the room temperature connections) are plotted in figure 8. The total resistance is around 530Ω , about 0.5% of the resistance of the CBT circuit.

The onset of superconductivity is visible below 2 K in the temperature dependence (the T_C of bulk Al is 1.2 K, and this is explored further in section A.4), however the change in resistance between ~ 2 K and 15 K is less than 1Ω .

The start of a superconducting transition is also observed in the field dependence at 1.5 K below about 300 mT. Excluding this, the resistance of the circuit increases by only around 10Ω between 0 T and 12 T, a change of $\sim 2\%$. This difference is around 0.01% of the resistance value for the CBT, and will have only a small effect at low temperatures, where the sensitivity of the CBT is highest.

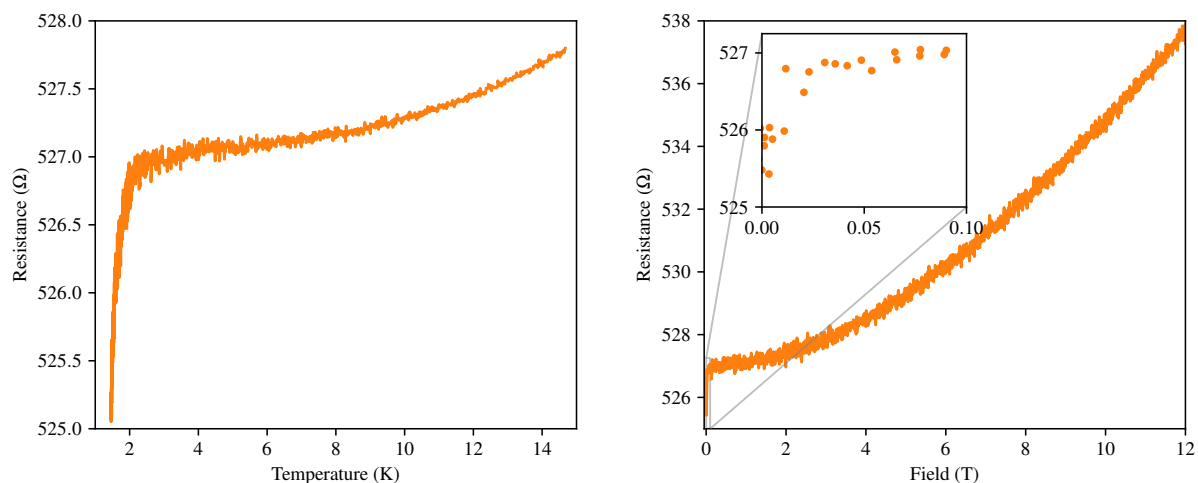


Figure 8: Left panel: temperature dependence of the resistance of the Al meander circuit at zero field when cooling. Cooling rate approximately 5 mK s^{-1} , lock-in amplitude varies linearly between 0.18 mV at 1.46 K and 1.8 mV at 14.6 K. Delay time between measurements = 3 s, frequency = 73 Hz, averaging time = 1 s. Right panel: field dependence of the resistance at the base temperature of the system (approximately 1.5 K). Frequency = 73 Hz, delay time between measurements = 1.5 s, lock-in modulation amplitude = 0.15 mV. Field sweep rate $\sim 4.2 \text{ mT s}^{-1}$. Inset: region between 0 mT and 100 mT, showing the onset of superconductivity.

A.4. Superconducting transition

To confirm the superconducting transition in the Al meander, the LCC20 chip holder was transferred to a HelioxVT (sorption pumped ^3He refrigerator probe for the TeslatronPT). This allows for measurements down to ~ 300 mK, and shows clearly, in figure 9, the expected transition at 1.2 K. The residual resistance value of around $100\ \Omega$ is determined by the resistance of the probe wiring and is about 20% of the total meander circuit resistance.

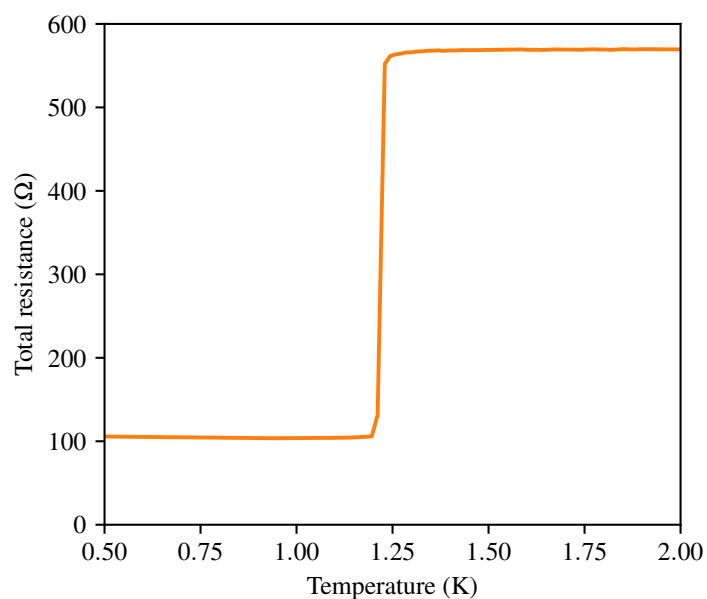


Figure 9: The two-wire resistance of the Al meander circuit (as inferred from the reciprocal of the dI/dV measurements). Below the superconducting transition the resistance value reflects that of the wiring to and from the instrumentation.